SPARK
REPORT

STRATEGIC
PLANNING
FOR
APPLIED
RESEARCH
AND
KNOWLEDGE

Science
Council of
British
Columbia

SUPERCONDUCTIVITY COMMITTEE

PLANNING REPORT

PREPARED FOR
THE SCIENCE COUNCIL OF BRITISH COLUMBIA
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EXECUTIVE SUMMARY

Superconductors are materials that can sustain extremely large electric current densities without power loss; that can maintain these currents even in the presence of very large magnetic fields and that can be configured into devices uniquely sensitive to magnetic fields and other electromagnetic signals.

These properties of superconductors are only obtained when the material is cooled below its critical temperature. Prior to 1986, the highest critical temperature was about 20K or about 270 degrees centigrade below room temperature. In 1986, a significant breakthrough occurred bringing this temperature up to about 40K and more recently, it has been raised to above 90K, which is above the temperature of liquid nitrogen. Major research efforts are now underway around the world searching for materials that will raise the critical temperature even more and also looking for innovative applications for superconductivity.

Worldwide markets in superconducting technology are growing rapidly. In 1986, the total market was estimated at $211 million whereas the estimate for 1990 is $920 million. This forecast was based on the conventional low temperature superconductors and does not factor in the many new applications that should arise from the enhanced economy provided by the recently discovered high critical temperature materials.

Applications for superconductivity include the use of thin films in microelectronics, low loss signal transmission, tunnel junctions, and sensitive magnetic detectors which are used in medicine and geophysics. Superconducting electronics is projected to find increasing application in ground and space based communication systems. Superconducting magnets are widely used in magnetic resonance imaging in hospitals and also find application in magnetic separation, magnetic levitation and propulsion (trains, ships, etc.), and for energy storage and transmission by power utilities.

Research in superconductivity in British Columbia has been focussed at UBC, SFU, TRIUMF, and 4 or 5 companies. These organizations have developed a small group of highly qualified researchers, some high technology laboratories and a focus on thin film and electronic applications.

The potential market for superconductivity warrants much more effort in British Columbia. However, the possible applications are many and varied. We cannot possibly address them all. The committee sees a need for a focussed and coordinated effort to ensure our share of this expanding area.

The committee recommends the creation of an Applied Superconductivity Institute that would coordinate applied superconductivity research. This institute would attract and fund leading researchers; focus research on the production of thin films that would find application in microelectronics and magnetometry; fund joint university industry projects for innovative applications and generally raise the profile of superconductivity in British Columbia.

The committee strongly believes that support for this institute now will enable the establishment of an excellent core group of research scientists and an enhanced industrial base on which economic development can be built. Superconducting technology is in its infancy and immediate action should yield large benefits in the future.

1. INTRODUCTION

The Science Council of British Columbia established a series of sectoral planning committees in early September 1987, based on its already existing AGAR Grant committees, to identify opportunities for improving the application of science and technology to the economy of British Columbia. These committees comprise representatives of industry, universities, institutes and colleges, research institutions and government, and are to develop specific sectoral plans for the application of science and technology. The recommendations of each committee will then be reviewed and priorities established by Science Council and integrated into overall plans for science and technology by the Premier's Advisory Council on Science and Technology and by the provincial government.

These sectoral plans are aimed to identify key strengths and weaknesses and to make broad recommendations. Detailed investigations of specific opportunities or resolution of problems identified will occur subsequently once priorities have been established.

The Science Council initiative is particularly timely in the case of superconductivity. The recent discovery of superconductors that operate at relatively high temperatures has generated an enormous amount of research and they promise to have applications in almost all branches of high technology. The following report describes present British Columbia university and industry activities in high-T_c superconductivity. Potential applications are also described and specific recommendations are made to enhance the British

Columbia effort in high-T_c superconductivity research. This enhanced effort should ensure that British Columbians will benefit from the inevitable technological advances that will occur in this area.

The following individuals were members of the Superconductivity Planning Committee:

Max Burbank	CTF Systems Inc.
Jess Brewer	Department of Physics, UBC
James Carolan	Department of Physics, UBC
Alistair Fife	CTF Systems Inc.
Walter Hardy	Department of Physics, UBC
Bretislav Heinrich	Department of Physics, SFU
Chuck Irwin	Department of Physics, SFU
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Dick Scarth	B.C. Hydro
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2. BACKGROUND INFORMATION

2.1 CONVENTIONAL (LOW-T_c) SUPERCONDUCTORS

Superconductors are materials which:

(a) can sustain extremely large electrical currents densities without energy loss,

(b) can maintain these current densities even in the presence of very large magnetic fields, and

(c) can be configured into devices uniquely sensitive to magnetic fields and other electromagnetic signals.

These properties of superconductors are only obtained when the material is cooled below its critical temperature (T_c). Prior to 1986, the highest critical temperature available was about 20K or about 250C below room temperature. In practice, this meant that superconducting devices had to be cooled with liquid helium to a temperature of 4.2K (-269C), a process which is cumbersome, complex and very expensive. The primary applications of normal or "low-T_c" superconductors have been in the areas of superconducting electronics and magnets.

Despite the expense and other disadvantages incurred in cooling with liquid helium, commercial markets have been developed which exploit the unique properties of superconductors. These are, for example, in the areas of ultrasensitive magnetic field sensing using magnetometers based on Superconducting Quantum Interference Devices (SQUIDS) and in medical diagnostics, such as Magnetic Resonance Imaging (MRI). Further details on superconducting electronics can be found in a recent article by M. Nisenoff of the U.S. Naval Research Laboratory (Appendix A).

2.2 HIGH-T_c SUPERCONDUCTORS

In 1986, at IBM in Zurich, Bednorz and Muller discovered a new ceramic material ($LaSrCuO_x$) which was superconducting at a temperature of about 40K, almost twice the previous highest T_c (23K). They received the 1987 Nobel Prize in Physics for this discovery. The subsequent research race has resulted in the discovery of new materials in 1987 and 1988 which are superconducting above the temperature of liquid nitrogen (77K (-196C)). There are three groups of superconducting ceramics of current interest:

1. T_c = 93K (-180C): "1-2-3": $RE_1Ba_2Cu_3O_7$
   where RE = a rare earth element such as
   Yttrium, Holmium, Dysprosium, etc.
2. T_c = 110K (-163C): Bismuth compounds such as $Bi_2Sr_2Ca_2Cu_3O_x$
3. T_c = 125K (-148C): Thallium compound
   $Tl_2Ba_2Ca_2Cu_3Ox$

Raising the temperature of operation of superconductors greatly reduces the expense and simplifies many other problems that are associated with cooling. For example, high-T_c superconductors can be cooled with liquid nitrogen (approximately 30 cents per litre) instead of liquid helium (approximately $8.00 per litre). When one also considers the resultant simplification that is involved in designing the refrigerators and device housings, it is not surprising that it is widely anticipated that the commercial applications of superconductors will multiply enormously in the very near future. The fact that the world reserves of helium are very limited also adds a sense of urgency to the development of high-T_c superconductors and their applications. Further details can be obtained from a recent article in TIME magazine (Appendix B). To realize this growth, however, a great deal of research and development remains to be done. Present activities in the world-wide high-T_c research community include:

(a) development of adequate theoretical models for the high-T_c superconducting ceramics;

(b) development of still higher T_c's with new chemical formulations;

(c) optimization and stabilization of the material properties in order to produce practical geometries such as films and wires which can then find applications in areas such as superconducting electronics and magnets, etc.

(d) Identification and investigation of novel applications of superconductivity.

3. ECONOMIC POTENTIAL

3.1 CANADA IN A GLOBAL HIGH TECHNOLOGY MARKET: THE COMPETITIVE ENVIRONMENT

The Canadian and British Columbia economies remain highly dependent upon traditional resource markets and pricing. Both are "small open economies" and are "price-takers" not "price-setters". Therefore, British Columbia is facing tougher and tougher competition from developing countries because of a dependence upon labour-intensive resource processes. This feature is becoming even more pronounced as world markets become dominated with new technological innovations that further reduce both price and traditional dependencies on primary resource products.

Most progressive industrial nations are making the transition towards a more diversified economy, with job creation predominantly in smaller firms and the service sector. This trend is largely driven by technological advances in fields associated with or relating to advanced systems based on the discovery or fabrication of new materials. There are several very dramatic indications of the need for B.C. to respond in an equally dramatic fashion to remain competitive in an accelerating technological and information era.

The world markets for the applications of superconducting materials has been predicted† to expand at a very rapid rate over the five year period 1986-1990. Superconducting magnets are used in Magnetic Resonance Imaging machines in hospitals and this market is expected to grow to 350 million dollars by 1990. If funded, the Superconducting Super Collider (for high energy physics experiments) will require 10,000 superconducting magnets at a total cost of approximately $300,000,000. The utilization of superconducting devices in electronic applications is also growing very rapidly. These applications include signal processors, SQUID Magnetometers for geophysical surveys and medical diagnostics, logic circuits, sensors and computers. It should be noted that this growth estimate (which is summarized in Table 1) is based on anticipated applications of conventional low-T_c superconductors. The advent of high-T_c materials could accelerate these estimates enormously. For example, the amount of money spent only on research and development of high-T_c materials and prototype devices already exceeds $100,000,000 annually. A comparison with the 1986 activity is also presented in Table 1.

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†"Superconductors - Exploiting Electronics and Computing Applications"; SEAI Technical Publications, 1987

TABLE 1

Applications	1986 U.S. dollars	1990
Medical Imaging	$150 million	$350 million
High Energy Physics	25	300 (SSC)
Research and Development	5	100 (High-T_c)
Electronics	20	150
Energy Research	10	10
High Speed Trains	1	10
TOTALS:	$211 million	$920 million

3.2 RESEARCH AND DEVELOPMENT AND JOB CREATION

The impact of technology on employment is becoming an increasing challenge in British Columbia. There are several recent reviews on the topic which include a report by the Economic Council of Canada on the Employment

Effects of Technological Change, and Training and Human Resource Requirements in the British Columbia Electronics Industry. There is no question that there is some job loss and dislocation as a result of implementation of new technologies; however, it is equally evident that there has been reciprocal job creation over the past several decades that is increasing in the high technology-related industries and service sector at a rate greater than the rate of overall employment growth. It is equally evident from the NSERC Five Year Plan that Canada is not producing M.Sc. and Ph.D. scientists and engineers at a sufficient rate to meet industrial demand and Canadian needs in order to compete effectively with other industrialized countries. There is also strong evidence† to suggest that research intensive industries strongly out-perform industries that do not do extensive research and development. This situation is further compounded by the comparative deficiency of research and development investment in British Columbia with respect to other provinces in Canada, and in Canada with respect to other industrialized countries.

In terms of the government leverage on its investment, a recent study for the Ontario Ministry of Industry, Trade and Technology suggests that for every one dollar of provincial funding supplied to centres of excellence in Ontario, $4.50 was returned in incremental provincial revenues within the first five years.

3.3 UNIVERSITY RESEARCH AND TECHNOLOGY TRANSFER

The Canadian and British Columbia university research and educational systems are ranked among the very best in the world. A discussion of the

† MOSST Federal Scientific Activities; Innovation and Technological Change in Canadian Industries, Economic Council of Canada Discussion Paper No. 176, 1980

research programs at universities in British Columbia is available in several documents including the university research reviews, the university five year plans, the Canadian 5th Generation Research Plan, and the university submissions to the Funds for Excellence in Education. A particularly lucid report on the role and function of the universities in providing research and education in the province was written by P.A. Larkin, and later augmented with further administrative and financial considerations.

The importance of the universities in providing technology transfer with industry has also been underscored by many authors who advocate closer cooperation among universities, industry and government as essential to the efficient transfer of technology and better training of more people in critical disciplines. This is particularly important in both Canada and British Columbia which conduct a far greater amount of research in universities rather than in industry in comparison with almost all other developed industrialized nations.

This concept has been initiated and fostered in British Columbia via the Discovery Foundation through its research parks on the campus of each of the British Columbia universities and the recent institution of University/Industry liaison offices within each of the British Columbia universities. Graphic evidence that the university-industry technology transfer is effective is illustrated by the number of spin-off companies and sales of products and services in British Columbia.

> "U.B.C. has generated over fifty spin-off companies that grossed sales of $85 million in 1985. Our industrial contract research has doubled in the past year to $3.4 million and continues to rise. Licencing agreements for U.B.C. inventions with industry are an important and growing contributor to university revenues." (D. Strangway, 1986). Direct industrial employment was 1,640 and indirect employment approximately 800.

Therefore the universities are well poised to be the Engine of Recovery in British Columbia by coordinating their collective strengths in the fields of advanced materials and being the prime agents for technology transfer to industry. The recent discovery of high-T_c superconductors provides a unique opportunity for British Columbia universities, industries, and government to become involved at the outset in a rapidly developing and potentially very important new technology. A coordination and focus of the research and development effort in British Columbia is essential, however, if the province wishes to realize the economic benefits that will accrue from the many applications that are envisaged for high-T_c superconductors. Several of these applications are discussed in the following sections (4.1, 4.2, 4.3, 4.4).

4. APPLICATIONS OF SUPERCONDUCTORS

4.1 INTRODUCTION

Most applications of superconductivity (Fig. 4.1.1) fall under two broad classifications:

- Superconducting thin films and devices
- Superconducting wires and devices

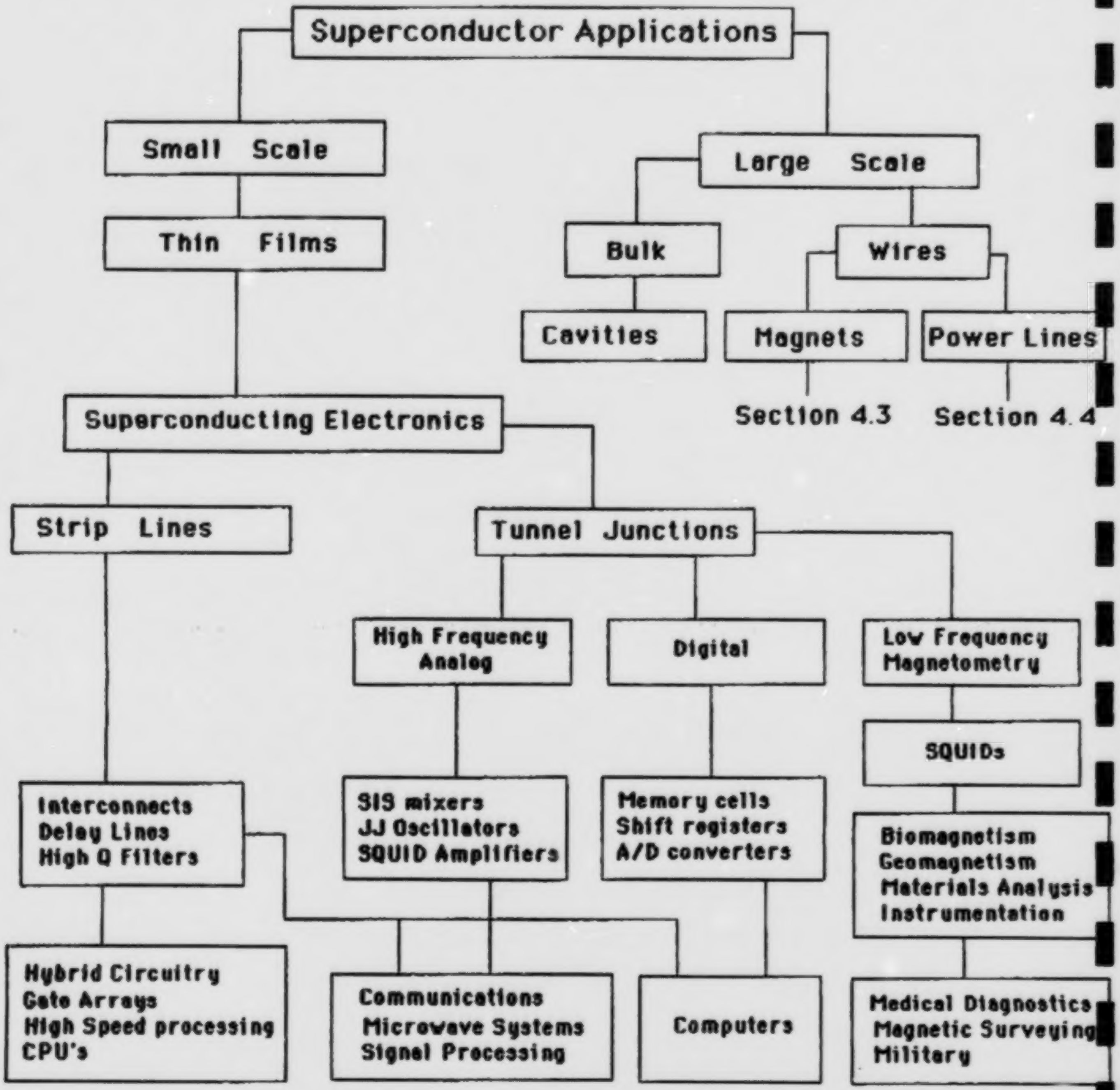
Superconducting thin films are usually related to physically small electronic devices characterized by very low power dissipation, very high speed and very high sensitivity. The superconducting wire applications are generally related to physically large structures such as superconducting magnets and power transmission lines with high fields and current densities.

In addition, there is an area termed RF superconductivity related principally to high-Q cavities for particle accelerators, but which also have potential application for electronic and power devices.

In reviewing the various applications in Table 4.1.1, the area of superconducting electronics is considered to have the greatest potential near-term benefits to the British Columbia economy. In the longer term, superconducting magnets must also be considered, with applications to medical diagnostics, mining and chemical industries.

In what follows, brief descriptions will be given of applications of interest, existing capabilities and the future major opportunity areas for B.C.

Figure 4.1.1: Summary of Applications of Superconductors



4.2 SUPERCONDUCTING ELECTRONICS

The term "superconducting electronics" has been coined to describe a relatively new branch of electronics, which exploits the remarkable properties of superconductors. The relevant properties include:

- vanishingly small resistance from D.C. to very high frequencies
- constant phase velocity from low to very high frequencies
- quantum mechanical tunneling effects in superconducting junctions
- flux quantization in superconducting rings

It is possible to fabricate from superconducting materials passive and active devices which have electronic properties entirely unavailable or superior to those fabricated from resistive materials. These include low loss signal transmission lines for microelectronic interconnects (inter- and intra-chip), magnetometers, mixers, high-Q cavities and filters, high speed switches, memory cells etc.

4.2.1 Low Loss Signal Transmission Lines

Although superconductors have zero dc electrical resistance, they do display a surface resistance which increases with the square of the frequency. Nevertheless at 1 GHz, the surface resistance of a superconductor such as Nb can be 100,000 times less than the surface resistance of copper at room temperature. The surface resistance for the new high-T_c materials is projected to be even lower at the same frequency and temperature.

The "zero" resistance of superconductors, means that there is very low heat dissipation and attenuation for high speed signals travelling along superconducting transmission lines. The constancy of signal phase velocity (zero dispersion) also results in very little distortion or "smearing" of the signals. These nearly ideal features allow the fabrication of narrow strip lines interconnecting very high densities of elements on complex chips. They also simplify chip layout via long, low loss interconnects. Since most of the area of LSI or VLSI chips of present (semiconductor) technology is occupied by interconnect lines of resistive metal, there is considerable interest in exploiting superconductors for this application for future generations of high speed devices.

Additionally, there is great interest in the development of superconductor-semiconductor hybrid devices which can exploit the best features of both technologies. For example, Gallium Arsenide and Silicon device properties improve on cooling with their optimum behaviour at temperatures in the neighbourhood of 100 K. If semiconductor elements operating at liquid nitrogen temperatures (77 K) can be successfully interconnected by high-T_c superconducting strip lines, then significantly higher element densities can be achieved and thus higher cycling speeds.

The area of low loss signal transmission lines is of considerable interest to a number of B.C. microelectronics companies.

4.2.2 Superconducting Tunnel Junction Systems

A superconducting tunnel junction consists of two superconducting regions which are separated by a very thin insulating barrier (a Superconductor-Insulator-Superconductor or SIS structure). Under certain conditions, which result from the quantum mechanical nature of the superconducting state, current can flow or "tunnel" through this barrier.

These tunnel junctions can display unique properties. If the tunnel barrier is sufficiently thin, the device becomes a Josephson Junction (JJ) which has found application in a wide variety of electronic functions (Fig. 4.1.1).

- Low Frequency Magnetometry - SQUIDS
- High Frequency Analog devices - SIS mixers, amplifiers
- Digital applications - memory cells, high speed A/D converters

4.2.3. SQUID Magnetometry

The term "SQUID" refers to Superconducting Quantum Interference Device and is an electronic structure which utilizes Josephson tunnel junctions and a phenomenon called flux quantization to achieve unprecedented magnetic field activity. In fact, SQUIDs represent the most sensitive sensors of magnetic field and field gradient which have yet been invented and provide at least 100 times more sensitivity than other technologies. (It is worth pointing out that SQUIDS have found application not only as magnetic field sensors but also as high frequency amplifiers (up to about 1 GHz), and memory cells and shift registers etc., for superconducting computer applications (sections 4.2.4, 4.2.5).

Applications of SQUIDs to low frequency magnetometry include the following areas:

- Biomagnetism
- Rock magnetism and susceptometry
- Geophysics (land based and airborne survey)
- General laboratory instrumentation
- Corrosion detection and kinetics
- Detection of flaws in circuit boards and chips
- Detection of problems in subsurface piping

The most important of these applications of SQUIDs in magnetometry is considered to be Biomagnetism, which is discussed in the next section. There is some commercial activity in this area already in B.C.

4.2.3.1 Biomagnetism

Due to their unique magnetic field sensitivity, SQUIDs may be used to measure the magnetic fields associated with living organisms, primarily those of the human body. These measurements have emerging clinical applications now under study around the world. The biomagnetic fields are generated as a direct result of electro-physiological currents flowing in the brain, heart, muscles, and other regions, or by the presence of magnetic materials in various organs such as the lungs and liver. The most important feature about SQUID biomagnetic measurements is that they are entirely non-invasive.

Biomagnetic measurements have been used to probe dust clearance from the lungs of miners, welders, etc. and also to non-invasively monitor the level of iron in the liver for diseases such as hemochromatosis (iron overload). The accuracy of the SQUID method is as good as a painful clinical biopsy which involves removal of live tissue for subsequent iron level determination.

The greatest area of interest in biomagnetic measurements has been in brain research (MEG - MagnetoEncephaloGraphy). Special emphasis has been placed on the non-invasive recording of magnetic signals related to neural disorders such as epilepsy or evoked stimuli where the brain response is recorded for an external input signal - visual, oral, auditory, or mechanical. Analysis of the SQUID signals related to epilepsy has resulted in the ability to localize the epileptic source in the cortex to within a few mm.

The thrust of much of the MEG research has been to try and use the SQUID biogmagnetometer to understand how the brain functions and processes information. Within the brain, differential changes can occur on the order of milliseconds. For example, changes generated from brain stem regions occur as quickly as 6 msec after input of visual or auditory information. A spectrum of signals can occur over intervals of a few milliseconds to a few seconds.

Use of a multichannel SQUID system allows measurement of brain signals with good temporal and spatial resolution and promises to provide fast, accurate and non-invasive information about the brain. Clinical versions are presently under development with up to 100 separate SQUID channels.

The R&D phase of SQUID-MEG is expected to continue for the next 2-5 years and then a much expanded demand for multichannel SQUID MEG systems can be projected in the Medical Imaging market. Growth of this market can be viewed as occurring in similar fashion to the growth of the markets for Digital Radiography, Computerized X-ray Tomography (CAT) and Magnetic Resonance Imaging (MRI).

4.2.3.2 Other SQUID Magnetometer Applications

SQUID magnetometers have been developed for measuring the magnetic character of weakly magnetic samples of organic or inorganic origin. For example, the study of geological rock samples from widely dispersed field sites has been important for the development of theories of continental drift. The edges of continental plates are related to regions of enhanced mineralization.

The susceptibility of samples provides information about their physical and chemical structure and SQUID instruments have been developed for measuring their susceptibility in the temperature range 3-300 K.

SQUID magnetometers and gradiometers have been developed for field installation and land-based or airborne mobile applications. The unique sensitivity of the SQUID sensors allows compact multichannel systems to be fabricated.

Various instruments based on SQUID sensors have been or are still under development. These include sensitive voltmeters, inductance bridges, gravity measurement devices.

A recent innovation has been the non-destructive monitoring by SQUID gradiometers of corrosion in metallic samples. Using SQUIDs, it is easy to detect the currents which flow on a metallic surface during corrosion attack. These currents may be detected long before any visual damage is evident. Thus the SQUID may prove to be a very useful tool in the reduction of corrosion in automobiles, ships, etc., a problem which costs billions of dollars annually.

Applications of miniature SQUID magnetometers as diagnostic tools for detecting flaws in circuit boards and possibly chips is also under study. These devices need to be miniaturized to improve spatial resolution. High T_c SQUIDS are attractive for this application since the SQUID sensor to circuit spacing can be reduced when compared with helium cooled systems.

4.2.4 High Frequency Analog Devices

The high speed, low loss and low power properties of superconducting circuitry are being exploited in a number of high frequency analog areas. These include:

- 70 GHz oscilloscope with a 10 ps rise time
- SIS mixers for microwave frequencies up to several hundred GHz
- High Q oscillators based on Josephson junctions
- High Q filters
- Low noise SQUID amplifiers for frequencies up to about 1 GHz
- Integrated superconducting microwave receivers
- Radiometers
- Signal processing - convolvers, correlators, spread spectrum communications

The most sensitive microwave mixers which have been developed to date are the superconducting tunnel junction (SIS) mixers which use an extreme non-linearity in the tunneling current versus voltage characteristic for their operation. SIS mixers are unique in that they can also provide conversion gain. This sensitivity has been demonstrated to frequencies beyond 100 GHz. The use of SIS mixers in microwave telescope receivers has been responsible for the recent improvements in sensitivity of astronomical observations for frequencies in the range of a few GHz to > 100 GHz.

Microwave receivers are under development in which almost all components are superconducting. These systems have superconducting antennas, strip lines, local oscillators, SIS mixers, intermediate amplifiers, filters, coils, etc. Their application area would be in satellite communications and military systems where size, weight, power consumption and sensitivity are extremely important factors.

This is an area of particular interest to astronomical research in B.C. The Herzberg Institute of Astrophysics (which includes DRAO, Penticton, and DAO, Victoria) is a member of an international consortium which is developing a superconducting receiver at 345 GHz for the James Clarke Maxwell Telescope on Mauna Kea, Hawaii. DRAO operates cryogenically cooled microwave receivers on its 26m radio telescope near Penticton and conducts research into methods of increasing the sensitivity of radio telescopes.

Filters fabricated from superconducting materials have demonstrated extremely high-Q bandpass which improves signal to noise ratios and increases channel density in a given frequency band. As communication frequency bands become more and more crowded, high-Q filtering capability becomes increasingly important. Superconductors appear to have the technological edge and should find application both in ground and space based systems.

4.2.5 Digital Devices

Josephson junctions of low-T_c materials such as Nb, display the best delay-power characteristic of any known switch (about 10^{-12} sec at about 10^{-6} watt for 2.5 micron technology). Although high electron mobility GaAs transistors (HEMT) can approach this switching speed with 0.25 micron technology, the power consumption per HEMT gate is 100 to 1000 times higher. The very low power consumption of the JJ allows high element packing densities and is thus especially important for ultra high speed computing where interconnect line length becomes important to CPU cycle time.

JJ circuits can be used as high speed memory elements, shift registers, analog to digital converters and counters and thus all the elements of a superconducting computer can be fabricated. Although IBM was an early pioneer in the JJ computer, good progress has been made in recent years by the Japanese, by using a superconducting refractory metal technology (Nb) which greatly improves yield, reliability and element uniformity. A 1 kilobit RAM fabricated using Nb JJ's has been recently reported by NEC of Japan.

4.2.6 Impact of High-T_c Materials on Superconducting Electronics

All applications which have been described above have been implemented using low-T_c technology with devices operating in or near liquid helium temperatures (4.2K). The single, major advantage of the high-T_c superconductors would be the operation of superconducting electronic devices at temperatures of liquid nitrogen or higher, which would greatly simplify the cooling problem, as well as open the door to hybrid superconductor-semiconductor technologies. The areas which will benefit most are those where system performance is at a premium and cannot be improved in any way other than by using superconducting materials and devices. Examples in the field of electronics would include lightweight, low power satellites for communication, astronomy, etc.

There has been significant progress in the area of high T_c superconducting electronic devices but considerable research and development remains. In the high-T_c SQUID area, there have been some rudimentary microbridge junctions and SQUIDs reported, but no group has succeeded in fabricating a well-behaved tunnel junction with two high-T_c electrodes separated by a well defined insulating barrier. All high-T_c SQUIDs fabricated thus far, including those from CTF Systems, have displayed rather large intrinsic noise levels - much larger than for equivalent low-T_c devices. This excess noise is being actively investigated at present.

Acceptable microwave properties have been reported for single crystals of high-T_c material. However, the surface resistance of polycrystalline samples is still too high for applications.

Thus, much work remains in the area of high-T_c superconducting electronics. However, progress in the past 12 months has been dramatic and large, well funded groups are attacking the various problems worldwide. If British Columbia is to capture its share of the potential market in superconductivity, then its university and industrial scientists must be part of the worldwide activity. This can only occur if reasonable long term funding can be put in place for superconductivity research and development.

4.3 SUPERCONDUCTING MAGNETS

4.3.1 Introduction

A conventional electromagnet usually has copper windings cooled by water in order to dissipate the Joule heating generated by the resistance of the copper. This heating and the need to remove it, generally limits the peak magnetic field from electromagnets to about 2 Tesla (20,000 gauss).

Soon after the discovery of superconductivity in 1911, it was realized that superconducting wire could be used to generate very large magnetic fields without consuming any power. However it was not until commercial superconducting wire based on the ductile alloy NbTi became available in the 1960's and 1970's that routine generation of magnetic fields in the 5-8 Tesla range could be achieved. By using other less tractable alloys such as Nb_3Sn in specially constructed windings, the peak fields have been raised to about 18 Teslas. The generation of these immense magnetic fields then allows applications which would be otherwise impossible.

Applications of superconducting magnets can be subdivided into four main areas:

- Research
- High energy physics
- Medical technology
- Industrial and Energy Technologies

Applications within these subdivisions are listed in Table 4.3.1. Almost all present applications use commercial copper or aluminum stabilized NbTi wire operating at 4.2-4.5 K with a few specialized very high field systems using Nb_3Sn. Superconducting magnets can be further classified according to size - small, medium and large scale and this is presented in Table 4.3.2 using a unit termed the Mega-Amp-meter. One Mega-Amp-meter is approximately equivalent to 10kg of standard CuNbTi composite wire in a field of 6 Teslas. Note that although the USA's SSC project has a very large scale, the actual size of the large number of individual magnets places them in the medium range.

TABLE 4.3.1

APPLICATIONS OF SUPERCONDUCTING MAGNETS

Research	Fusion (magnetic confinement of plasmas)
	Solid state research
	Materials research
	NMR in physics, chemistry and biological sciences
	Spectroscopy
	SQUID susceptometry
	Magnetic refrigeration
	Sub-micron lithography
Medium and High Energy Physics	Acceleration, focussing on particle beams
	e.g. SSC, TRIUMF's KAON factory
	Analysing particle beams
	Beam detectors e.g. cloud chambers
Medical Technology	Magnetic Resonance Imaging (MRI)
	Catheter guidance
Transportation Technology	Magnetic Levitation and Propulsion (MAGLEY)
	Motor drives for ship propulsion etc.
	Direct drives for ship propulsion
	Magnetic drives for assisting rocket take-off
Power Industry	Power conditioning
	Energy storage
	AC generators
	Superconducting rectification
	Current fault limiters
	MHD generation
Space Applications	Energy storage
General Industrial applications	Magnetic separation
	High resolution lithography

TABLE 4.3.2

SUPERCONDUCTING MAGNET CLASSIFICATION BY SIZE

CATEGORY	APPLICATION	SIZE (Mega-Amp-Meters)
Small Magnets (1-10MAm)	Research	1-10
	NMR Spectroscopy	1-10
	Magnetic Refrigeration	1-10
	SQUID Susceptometry	1-10
Medium Sized Magnets (10-100MAm)	Maglev	10
	MRI	10
	DC Motors	10-50
	Energy storage in space	10-50
	AC Generators	50
	Ship Propulsion	50
	Fault Current Limiters	10
	Magnetic Separators	20
	Accelerators	5-10
Large Scale Magnets	Large Bubble Chambers	300
	Large MHD Generators	150
	Future MHD Generators	2000
	Large Fusion Experiments	400
	Future Fusion Reactors	2000-5000
	Large Energy Storage	$>10^4$

In what follows only a few of the applications will be briefly discussed. There are several recent reports on the applications of superconducting magnets. One which is relevant at this time is the Argonne National Laboratory report #ANL/CNSV-64 entitled "Advances in Applied Superconductivity: A Preliminary Evaluation of Goals and Impacts" by A.M. Wolsky et al.

The use of superconducting magnets for transportation (MAGLEV) has been developed (in Miyazaki, Japan), to the level of operational tests of a three-car, 30 ton train which has reached speeds in excess of 400 km/hr on an elevated guideway. This technology is particularly suited to dense traffic corridors where noise disturbance and pollution must be kept to a minimum. Canada (Department of Transport) has a superconducting Maglev R&D program aimed for eventual implementation in the Toronto-Ottawa-Montreal corridor. This program involves scientists from NRC, universities and a local B.C. company - CTF Systems Inc. CTF is primarily involved in developing superconducting magnets for this project.

Another interesting application of superconducting magnets is for ship propulsion either by superconducting motor or by direct drive, a concept involving passage of current through seawater at right angles to an on-board superconducting magnet. The use of superconductors in motor construction allows considerable reduction of size and weight. However much development remains to fully exploit the technology.

Medical Resonance Imaging is a maturing technology which uses superconducting magnets for whole body imaging of soft tissue. Although installations in medical institutions are relatively expensive, MRI has become a well established medical diagnostic and research tool in the fight against cancer, heart disease, and multiple sclerosis. Smaller MRI imaging systems for limbs etc. may become available in the near future.

Magnetic separation involves the use of magnetic forces to remove magnetic particles from a large non-magnetic background mass flow. This technique has been used for many years and is termed high gradient magnetic separation (HGMS). The use of superconducting magnets with flux densities 10 or more times larger than available with conventional electromagnets greatly increases the separation efficiency and reduces the power consumption. There appear to be numerous areas of application for such separators in industrial separation problems including:

- purification of sand for the glass industry
- purification of clay for the kaolin industry
- desulfurization of coal (pyritic impurity)
- removal of steel filings from blast furnace effluent
- removal of ferrous impurities in food processing, chemicals and pharmaceutical industries
- biological separations
- separation of weakly magnetic materials from minerals
- concentration of weakly magnetic, small grained ores and replacement of polluting chemical flotation techniques.

4.3.2 Impact of High-T_c Materials on Superconducting Wires

The sudden discovery of materials which are superconducting at temperatures above liquid nitrogen (77K or -196C) has opened up the possibility of constructing superconducting magnets and devices which would operate at much warmer temperatures than is possible with present "low-T_c" (liquid helium) wires. This would simplify the cooling requirements and operation of superconducting magnets and reduce the operational costs by at least a factor of 10. These advantages of course rest on the assumption that the new high-T_c materials can be made to perform at least as well as the liquid helium counterpart while operating say at 77K.

Since liquid nitrogen is a relatively cheap, safe and inexhaustible material, technologies based on liquid nitrogen cooling would be much more acceptable and reliable than their liquid helium counterparts. In addition, liquid nitrogen closed cycle refrigerators are much more efficient and hence less power and capital hungry than the 4 K machines.

Fabrication of wires from the presently known high-T_c materials has proven to be complicated since they are ceramics and are brittle and anisotropic in properties. The achievement of high current densities with these materials in wire form is an elusive goal. However, impressive progress continues to be made on a worldwide basis and it may not be long before high-T_c magnets are a reality. This is projected to speed the implementation of the applications in Table 4.3.1.

4.3.3 Potential of Superconducting Magnet Technology for B.C. Industry

Applications of superconducting magnets in the small to medium scale range can be envisaged in B.C. One of the applications of superconducting magnets which has potential for B.C.'s resource based economy is magnetic separation technology, for example in coal desulfurization and mineral separation. There are recent industrial installations of such superconducting separator systems in a large U.S. kaolin plant, and also a South African coal mine for coal desulfurization.

A low-T_c liquid helium High Gradient Magnetic Separation (HGMS) system has operating costs for power consumption which are about 20% of the conventional HGMS (room temperature) system. The projected power operating costs for a 77 K high-T_c system are expected to be a factor of 10 lower. Thus large savings in operating power requirements are expected.

All superconducting magnets and ancillary equipment currently purchased for application in B.C. - hospitals (MRI magnets), research (universities, TRIUMF) are brought in from foreign suppliers. Since the KAON factory proposed by TRIUMF is expected to make extensive use of superconducting magnets, a spin-off industry involving superconducting magnet technology could be nurtured in the province by requiring that some of the Kaon Factory superconducting magnet requirements be supplied by local industry. This would provide the basis for further applications such as Magnetic separation, MRI, and various applications to the electrical power industry listed in Table 4.3.1.

4.4 POWER UTILITY APPLICATIONS

The two characteristics of superconductors that are of interest to a power utility are first, that they conduct electricity with virtually no losses and second, that they can produce strong magnetic fields with low energy expenditure. Direct power utility applications therefore include: electric power transmission, large electric power generators, magnetic energy storage and advanced energy technologies such as magnetic fusion and magnetohydrodynamics. The adoption of superconducting switches (Josephson junctions) to make faster computers would be an example of an indirect application.

Potential benefits of using superconductors result from utility cost reductions due to lower transmission losses, improved generator efficiency, reduced generator size, cost savings on underground transmission and faster computers.

The drawbacks will depend on the type of superconductor being applied. The superconducting metal alloys require cooling in relatively expensive and difficult-to-handle liquid helium. The high temperature ceramic superconductors on the other hand, can be inexpensively cooled in liquid nitrogen but up to now they have shown low current carrying capacities at these temperatures and furthermore ways must be found to fabricate these brittle ceramics into flexible wires and other usable forms. In some applications, for example electric power generators, the switch from liquid helium to liquid nitrogen cooling may have little effect on economic feasibility because coolant and refrigeration costs are small compared to overall costs.

The timeframe for the development of superconductors for application in the electrical power field is thought to be at least 5 to 10 years, perhaps decades. Even after development to the commercial stage, application in some utility systems may be further delayed by large capital costs associated with conversion.

Electric power transmission lines and generators are possible long term applications of superconductors in the B.C. Hydro system. Magnetic energy storage for future load leveling will probably not be cost effective because relatively inexpensive hydroelectric peaking plants are available. Magnetic energy storage could be used to help maintain transient stability of the generators in the event of a transmission system fault but it is unlikely that such devices would be less expensive than the breaking resistors currently being used.

5. PRESENT RESEARCH AND COMMERCIAL ACTIVITIES IN BRITISH COLUMBIA

5.1 HIGH-T_c RESEARCH AT UBC

Research on high-T_c superconducting materials began at UBC in February 1987, and about 13 faculty members are currently committing from 10% to 70% of their time to this project. Approximately the same number of students and Post Doctoral fellows are involved. Except for Professors Carolan and Williams of Physics, none of the people involved had direct experience in superconductivity research. Our general objectives are (a) to keep up with the enormous volume of information resulting from the unprecedented international effort, (b) to mount a local research effort that is as vigorous as possible, (c) to look for patentable ideas in the area of raw compounds, processes and novel uses of the materials, and (d) to assist local companies in whatever ways that are appropriate.

The work at UBC varies from the very basic to the highly applied. The contributions from the various groups are as follows:

5.1.1 Materials Preparation

5.1.1.1. Department of Metals and Materials Engineering

Professor Chaklader has extensive experience in ceramics and has focussed on various methods of preparing ceramic samples of the $YBa_2Cu_3O_x$ superconductor and its derivatives. In particular, his group is producing sputtering targets (for thin film deposition) for a local company (CTF Systems Inc.), which is currently the only Canadian supplier of superconducting device systems. Prof. Chaklader is also studying polymeric extrusion of superconducting wires and coils.

5.1.1.2. Physics Department

Professors Hardy and Carolan have set up facilities for production of ceramic samples of almost all of the new materials, in the form of 1/2", 3/4", 1" and 2" discs and short tubes, and now have extensive experience in the use of various crucible materials to minimize contaminations in the various compounds. Small single crystals of very high quality have been recently obtained, for fundamental studies. A special effort has been put into careful control of the oxygen content of the materials.

Routine sample characterization uses locally developed resistivity probes, the X-ray machines in Metals and Materials Engineering and Geology, and the magnetometer in Chemistry. The electron microprobe in Geology is an extremely powerful tool for chemical analysis. Detailed electrical measurements can be carried out using the facilities of Professor Carolan.

5.1.1.3. Thin Films

Professor Parsons' group uses D.C. Magnetron sputtering to produce thin films of the high-T_C materials, and to study their electrical properties. The group's films have been studied by Raman scattering at Simon Fraser, and a collaboration established with P. Grant and D. Inglis of NRC. The Parsons' group is currently working on methods to reduce the annealing temperatures required (presently 800°C) using plasma activation, in order to make the materials compatible with silicon technology. Other projects include measurements of the optical properties of the film over a wide range of wavelengths.

Professors Tiedje and Cline are assembling an electron beam evaporation system for production of thin films by an alternative method. Two of the constituents will be evaporated by the e-beam and one by thermal methods. They plan to set up an ion-beam milling system for patterning the films.

5.1.2 Theory

Professor Affleck's efforts are focussed on trying to understand the fundamental mechanism for superconductivity in the new materials. In particular, he is studying the consequences of the so-called Hubbard model, which at the moment seems to be the simplest theoretical model that contains the essential physics.

5.1.3 Muon Spin Rotation (MSR)

We are fortunate in having, at Triumf, one of the very best MSR facilities that exist in the world. MSR has turned out to be a very versatile probe of the microscopic magnetic properties of the new materials and the work at Triumf has attracted international attention. Samples from groups in Japan, from AT&T Bell, from McMaster University as well as from UBC have been studied.

5.1.4 Microwave Properties

Prof. Hardy is setting up a system to make measurements of the microwave losses in single crystals of the new materials. This is largely for basic studies but is also relevant to high speed circuitry using the new materials.

5.1.5 Collaborations with Outside Companies

CTF Inc. - has collaborative work with Chaklader in Metals & Materials Engineering and with Hardy in Physics (on magnetic shields made from the new material).

TIR - Hardy has an ongoing collaboration with Lorne Whitehead, President of TIR, on novel uses of superconducting materials.

Moli Energy - Carolan has done exploratory collaborative work with Dahn of Moli. Dr. J. Stiles of Moli is currently in residence at UBC Physics. His mandate is to look for new opportunities and is keeping a close watch on the field of high-T_c superconductivity.

5.2 HIGH-T_c SUPERCONDUCTOR RESEARCH AT SIMON FRASER UNIVERSITY

The research program in high-T_c superconductivity at SFU comprises both a fundamental component and a strong effort in what might be called applied or applications oriented research. We are carrying out both theoretical (Dr. G. Kirczenow) and experimental investigations on the basic properties of the materials. Hopefully, these studies will help to clarify the nature of the physical mechanism that is responsible for superconductivity in these new materials.

Our applications oriented research effort is focussed on the properties of thin superconducting films that will be suitable for applications in magnetic detectors, sensors and microelectronics. In the latter case, a fusion of the superconductor and semiconductor technologies appears very promising. All applications, however, require thin films of materials in which the superconducting elements are either in the form of striplines or with a tunnel junction geometry.

The first step in this process will be the growth of high quality thin films. We hope to carry out this step in collaboration with Dr. R.R. Parsons at UBC and CTF Systems of Coquitlam. At SFU, films will be grown by Dr. S. Gygax using electron beam coevaporation. Dr. Parsons and CTF both grow films using sputtering techniques. We will also attempt to grow films on Si substrates and the development of an appropriate barrier layer (to prevent interdiffusion of Si and superconductor) will be an early goal. Tunnel junctions fabricated with insulating oxide layers or based on the proximity effect will be the next goal. Initially, the well-studied compound, $YBa_2Cu_3O_y$, will be used as the superconducting material which will have to be protected against deterioration due to oxygen loss. It is anticipated, however, that other materials such as the recently discovered Bi-Sr-Ca-Cu-O system will also be investigated and other substrates such as GaAs will be utilized.

A number of techniques and facilities are available at SFU for a determination of the properties of the superconducting materials and films. The critical temperature and other superconducting properties of the films will be determined from resistivity and magnetic measurements by Dr. S. Gygax. The basic crystalline structure will be monitored using X-ray diffraction and a more detailed knowledge of the local structure will be derived from a novel glancing incidence EXAFS technique (Dr. D. Crozier). Additional information can be obtained from Far Infrared Reflectivity experiments (Dr. B. Clayman) and from Raman Scattering experiments (Dr. C. Irwin). These optical techniques can also be used to investigate and monitor the vibrational and electronic properties of the compounds and, in addition, yield information of their chemical composition. Finally, our Surface Physics Laboratory (Dr. B. Heinrich) provides us with exceptionally powerful tools for the analysis of the chemical composition of the materials and for the study of the semiconductor-superconductors interface. These include the ability to carry out XPS and Auger analysis on the materials. The Scanner Auger Microprobe and Secondary Ion Mass Spectrometer will be used to investigate composition as a function of depth and as a function of position on the film.

In summary, we plan to grow thin films of superconducting material and fabricate devices from these films. We will use the many techniques at our disposal to study the basic physical properties of the materials and films and will use the results of these studies to optimize growth parameters and device characteristics. Throughout this process, we hope to continue to collaborate with local companies, such as CTF Systems and Microtel Pacific Research, who will be the eventual users of the end product of our research.

5.3 CTF SYSTEMS' POSITION IN SUPERCONDUCTIVITY

CTF Systems is involved in two principal areas of superconductivity:

- Superconducting Electronics
- Superconducting Magnets

The dominant company activity has been in the area of development and applications of Josephson-Junction-based superconducting electronics, including SQUID magnetometers and gradiometers. CTF is one of a handful of high technology companies world wide, supplying commercial SQUID instrumentation. Specifically, the company develops and markets state of the art SQUID based technology to the areas of:

- Biomagnetism
- Geomagnetism
- Rock Magnetism
- General laboratory instrumentation

CTF Systems is the only Canadian company active commercially in this field and has supplied the second largest number of SQUID installations to a demanding world market. The company is vertically integrated, and has developed internally its own market driven technologies in:

- thin film Josephson junctions
- thin film SQUID sensors
- low magnetic noise dewars (with or without cryocoolers),
- cryogenic composites
- low noise analog and digital electronics, robotic gantries and
- software for control, data acquisition and processing

Several years ago, the company decided to invest heavily in thin film superconducting technology and now has extensive in-house experience in production of high quality, thin film Josephson tunnel junctions, SQUIDs, strip lines and planar coils. This technology has application to both low frequency and high frequency (microwave) superconducting electronics.

With regard to the new highly critical temperature superconductors, CTF is actively developing materials and electronic devices (thin film and bulk $YBa_2Cu_3O_x$) for operation at elevated temperatures. This work involves collaboration with local university groups interested in high-T_c research (UBC Physics, UBC Metals and Materials Engineering and SFU Physics). Highlights of this activity include development of:

- Sputtered thin films of $YBa_2Cu_3O_x$ with Tc(R=0) about 85 K.
- Thin film microbridge junctions and strip lines from these films.
- Prototype high-T_c SQUIDS which operated up to about 70K.
- Bulk structures such as thick walled cylinders of $YBaCuO_x$ for shields with T_c's about 85K.
- Superconducting "inks" for thick film applications with T_c's in the range 80-85K.
- Superconducting wires of diameter about 0.8mm with T_c about 90K. Critical current densities have been low.

Both the low and high-T_c expertise which has been developed is providing expanded opportunities for the company both in R&D and commercial markets.

The area of superconducting magnet development has represented about 10% of the company's activities during the past few years. The goals have been to develop magnet technologies and cooling systems suitable for application to areas of transportation such as MAGLEV trains and ship propulsion via superconducting motors. This work has recently resulted in the development of lightweight solenoidal and racetrack shaped superconducting magnets which display stable operating characteristics at overall current densities of about 350 Amp/sq.cm. and peak fields of about 7 Teslas.

5.4 HIGH TEMPERATURE SUPERCONDUCTIVITY AT QUANTUM TECHNOLOGY

Quantum Technology Corp., founded in 1981, is a supplier of cryogenic equipment for scientific applications. The company designs and builds cryocoolers (cryogenic refrigerators) in British Columbia for sale on a worldwide basis. Systems include open and closed-cycle refrigerators covering the temperature range from 2K to 300K. Custom interfaces, such as optical access ports, narrow tails for external magnets and special sample holders as well as vacuum systems and temperature controllers are available with our systems.

In response to the advent of high temperature superconductivity, Quantum Technology Corp. quickly advertised, designed and built special instrumentation for scientists doing research in this new field. This included a high-T_c superconductor characterization cryostat as well as sample holders for both electrical resistivity and A.C. magnetic susceptibility measurements. Additional instrumentation is currently under development.

The existence of high-T_c superconductors will also result in useful instruments such as detectors, mixers, and sensors based on the new materials. They will still require cooling in the range 80K to 10K for optimal performance (low noise figure). At present, commercially available refrigerators covering that range are large, noisy and expensive ($10,000 - $20,000). There are a number of new technologies being developed which will result in much lower cost and more reliable cryocoolers. Quantum Technology Corp. would like to be the first in the world with a reliable cryocooler product for this market.

5.5 SUPERCONDUCTIVITY INTERESTS OF TECHWARE SYSTEMS

5.5.1 History and Traditional Thin Film Market

Techware Systems was formed in 1983 to exploit developments made by the UBC Department of Physics regarding automation of vacuum equipment and thin film processes. These processes are used by high technology materials industries worldwide, to manufacture microscopically thin layers of active materials on substrates of all natures. Thin films are commonly found on semiconductors, optical filters, magnetic and optical media, windows, cutting tools, turbine blades, and other devices. Thin film technology is a multi billion dollar annual activity, with strategic contributions to the electronics, computer, communications, optics, military, aerospace, and other technology based industries.

5.5.2 Participation in the Traditional Market

Techware's PAL-68000 automation product includes computer and interfacing electronics, a flexible software package, and applications services. PAL-68000 is the only intelligent automation product targeted for the vacuum thin film marketplace. It is manufactured entirely in British Columbia. Units have been sold to a wide variety of Fortune 100 technology corporations, as well as a handful of universities and smaller and medium size companies.

5.5.3 New Superconductivity Equipment Market

In addition to the far term markets for applications of superconductivity identified elsewhere in this report, a near term market is anticipated in the supply of specialized instrumentation and other products to the superconductivity research community. This equipment market is expected to grow as superconductivity research matures and manufacturing begins; it is estimated elsewhere in this report to reach $500 million by 1990. As it is doing in other thin film markets, Techware Systems is seeking applications of its PAL-68000 automation system in superconductivity R&D, in order to gain the market knowledge and technical competence necessary to make it a prime contender for market share as the superconductivity processing equipment market matures.

5.6 T.I.R. AND SUPERCONDUCTIVITY

This company is pursuing a number of possible applications of superconductivity. Their interest is in transferring this technology to relatively simple and straightforward applications that could have high volume economic potential in a relatively inexpensive product. They are not pursuing complex high cost systems but are seeking products in the retail and light industrial markets.

5.7 MOLI ENERGY

This company, which has pioneered developments in storage battery design and production is pursuing possible applications for superconductivity in the battery area. They have a particular interest in reducing the size and weight of batteries to open up more applications for portable batteries. This can be accomplished by increasing battery energy density and by promoting the development of products with reduced power requirements. Electric vehicle batteries and small storage batteries for other commercial and industrial users are longer term goals.

6. STATEMENT OF NEEDS

Based on the review of superconductivity market potentials, the current status of research activities in British Columbia and the perceived priorities for this important area of activity, the committee identifies the following needs:

1. A significant increase in the number of highly qualified specialists focussing on superconductivity in British Columbia, in the universities and in industry. In addition, adequate equipment and space must be available for these researchers.
2. To initially focus the efforts of this increased group of researchers on the thin film and microelectronic aspects of superconductivity, where important applications are envisaged in the communications and medical sectors.
3. The coordination of effort of those involved in superconductivity research at the universities and in industry and the provision of resources to increase communication and awareness on this subject.
4. The stimulation of increased activity in industry in superconductivity by the encouragement and nurturing of individuals and companies with researched products and services so that these may be developed and marketed.
5. To coordinate the activities of the superconductivity group with the resource based sectors and to explore applications in these areas.

7. RECOMMENDATION

The Superconductivity Sector Planning Committee, having reviewed the global market prospects and current strengths in British Columbia regarding superconductivity, recommends:

THE FORMATION OF AN APPLIED SUPERCONDUCTIVITY INSTITUTE

The purpose, structure, proposed strategy of the Applied Superconductivity Institute (ASCI), objectives, and recommended activities of the proposed institute are discussed in this section.

7.1 PURPOSE

The British Columbia Advanced Superconductivity Institute (ASCI) will be established to foster cooperative research, education and applications in the field of superconductivity. Institute activities will be designed to build on existing university and industry strengths and to reinforce them. Mutually beneficial collaboration among researchers at the British Columbia universities, industries and government laboratories will be encouraged and supported through the provision of "interaction costs" for data and video communication and travel. The Institute will also exploit and develop collaboration amongst the British Columbia, Canadian and international research and development communities and industry through affiliated programs, contracts and joint research of mutual benefit. The Institute will improve educational opportunities for working professionals through the sponsorship of seminars, conferences and short courses.

7.2 STRUCTURE

The Institute will be governed by a Board of Trustees with senior representation from the provincial and federal governments, the University of British Columbia, Simon Fraser University, appropriate industries and other research organizations. An International Scientific Advisory Board comprised of world-class scientists and engineers will provide the Trustees with expert scientific advice and direction in the development of research program priorities.

7.3 PROPOSED STRATEGY OF THE ASCI

The number of people in British Columbia who are involved in superconductivity research constitute a relatively small group when comparisons are made with major institutions and/or consortia in the U.S.A., Japan or Europe. If the efforts of this group are aimed in all the various directions which comprise superconductivity research, their efforts would be spread very wide and their impact would probably be small. For this reason, it has been decided that the focus should be on a particular aspect of superconductivity research. It has been decided that this focus should be on thin film research. This decision was made for the following reasons:

1. There is, at present, a great deal of expertise in our universities and at CTF Systems in the growth, characterization and application of thin film superconductors. Thin films are grown by sputtering at CTF Systems and at U.B.C., and by electron evaporation at both SFU and U.B.C. Extensive facilities are available for surface and interface characterization in the Surface Physics Laboratory at SFU, and optical techniques are available at both SFU and U.B.C. A detailed account of the expertise and facilities that are present at the various institutions is presented in the previous section. It is clear, however, that we have a great deal of strength in British Columbia in the area of

thin film research. Building on this strength in a collaborative and coordinated manner will maximize the impact of our efforts.

2. It is anticipated that high-T_c superconductors will find their initial application in the area of microelectronics. Applications in this area have already been initiated and it is expected that the use of high-T_c materials will expand very rapidly (see table on page 7). It should be noted that thin film technology will be at the basis of all applications envisaged for electronics. For example, CTF Systems are presently working to develop sensitive magnetic detectors based on high-T_c SQUIDS (Superconducting Quantum Interference Detectors). These detectors are used in geophysical exploration and biomedical applications. Superconductors will also be used to provide high speed inter-connections, dispersion-free transmission and for signal processing (see section 4.2).

3. The new high-T_c materials are basically ceramic and most are quite brittle. It may, therefore, be quite difficult to fabricate wires suitable for power transmission, coils and transformers. There are also some questions concerning the economic savings to be realized by utilizing the new superconducting materials in the electrical power field. For these reasons, the timeframe for applications by electrical power utilities has been estimated to be greater than ten years. For further details, see section 4.4.

In summary, it appears appropriate for the members of the research community in British Columbia to coordinate and concentrate their efforts in the area of thin film superconductors. This goal not only enables us to build on present strengths but also places us in an area that is of interest and potential benefit to local industry. Members will, however, continue to develop and investigate new materials as they arise. If materials suitable for wire fabrication become available, the focus of the institute will certainly be extended to applications concerned with the transmission of energy and electrical power handling devices.

7.4 OBJECTIVES

The Applied Superconductivity Institute will fulfill its mission through exercise of the following major objectives:

I Develop an internationally recognized centre of excellence for the promotion of basic and applied research in superconductivity to complement and enhance research activities in the British Columbia universities and the private sector.

II Contribute to improving educational opportunities and related industrial programs in collaboration with the universities, the private sector and other institutions.

III Encourage and facilitate the transfer and exploitation of technology leading to industrial applications in the private sector.

OBJECTIVE I A Centre of Internationally Recognized Research Excellence:

A. Establish fellowships to attract outstanding research talent to the British Columbia universities, repatriate Canadian researchers, and reverse the out-migration of British Columbia graduates.

(i) Provide research environments and levels of support for Institute members that are internationally competitive, that are based on merit and reward research excellence, that have a reasonable measure of duration and security, and that can be sought through open competition by existing and new researchers in industry and university.

(ii) Assist in attracting outstanding Postdoctoral personnel to British Columbia through the provision of appropriate fellowships. Positions in university, industry and other research laboratories will be supported and joint appointments will be encouraged.

(iii) Provide support to assist in attracting outstanding international scholars on a visiting basis.

(iv) Contribute in attracting quality graduate students through the provision of appropriate scholarships. Graduate students will be encouraged to work on joint projects between universities, industry and other British Columbia laboratories.

B. Foster collaboration and coordination of superconductivity research within, between and among the participating British Columbia universities, other participating universities and associated Canadian and international institutions.

  (i) Develop efficient communication and electronic data networks between participating universities and institutions to encourage integration of research projects and assist in establishing a literature database.

  (ii) Contribute to defraying the interaction costs among researchers at British Columbia universities and participating institutions for data and video communications and travel, and thereby encourage beneficial collaboration and the sharing of equipment and facilities.

  (iii) Maintain short-lifetime library materials, literature database and conference facilities and conduct and support regular state-of-the-art seminars and conferences to foster interaction between researchers.

  (iv) To foster interaction and coordination with other rapidily growing sectors such as space, communications and the resource based industries and to explore possible applications in these areas.

C. Identify priority research areas and niches appropriate for British Columbia and develop responsive research strategies and programs.

  (i) Build on exiting university and industry research strengths and identify new market opportunities.

  (ii) Support and enhance the effectiveness of the significant investments already made in British Columbia universities.

D. Establish an international scientific advisory board to advise on the research directions for the Institute and to report on the quality and appropriateness of its programs.

E. Ensure collaboration and affiliation between the university and private sector through Institute research programs.

F. Demonstrate the importance of pure and applied leading edge research and the development of commercial applications to allow B.C. to remain competitive and to assist in the diversification of the economy and to provide bona fide investment opportunities for major corporate participants and partners.

OBJECTIVE II Improve Educational Opportunities and Related Industrial Programs in Collaboration with the Universities

A. Provide access to educational programs via the British Columbia Open Learning Authority and the British Columbia Knowledge Network and supplement the institutions via satellite teleconferencing, particularly as applicable to industrial and refresher courses.

Provide encouragement for top-level high school and college students on a provincial basis to work towards education and careers in superconductivity and its applications.

B. Provide condensed business refresher and intensive industrial applications (credit and non-credit) courses in superconductivity concerning the latest in new developments which are particularly applicable to managers and industrial systems engineers and other working professionals.

OBJECTIVE III Transfer of Technology to the Private Sector Leading to Industrial Applications

A. Ensure the effective affiliation, collaboration and sponsorship of industry in Institute planning and programs through membership on the Board of Trustees and by providing for appropriate levels of industrial affiliation and sponsorship within the Institute.

B. Encourage the enhancement of existing industries, development of new industry and industrial research and applications consortia for the application of R&D results derived from Institute research and as a source for new R&D projects.

   (i) Facilitate and assist in the preparation of team- or consortia proposals for Institute/-university/industry research.

   (ii) Encourage industries to become associated with the Institute and to participate in joint pre-competitive research projects which may be carried out on-site within British Columbia companies.

C. Form strong linkages with other technology transfer agencies including the University/Industry Liaison Offices established at each of British Columbia universities, the B. C. Science Council, the Discovery Foundation (Discovery Parks, Discovery Enterprise, Discovery Innovation Centre) and the B.C. Research Council.

7.5 RECOMMENDED INSTITUTE ACTIVITIES

1. To increase the number of talented personnel who are involved in applied superconductivity research and device development, the Institute will sponsor the following initiatives:

   (a) Industrial and University Research Associates Program

   The ASCI would provide funds to assist in attracting outstanding postdoctoral personnel to the industries and universities in B.C. These young scientists could have industry or university appointments or a joint appointment between the two.

   (b) Graduate Student Scholarships Program

   To attract outstanding students into the research programs of the Institute. The students could carry out their studies in either an industrial or university environment or could pursue a jointly monitored project.

   (c) University Research Fellows

   The ASCI would sponsor a University Research Fellowship (URF) program identical to the NSERC program that is to be terminated in 1989. This program would enable the universities to recruit outstanding young scientists into faculty positions and thus increase the number of B.C. scientists dedicated to research in superconductivity.

   (d) Visiting Scientists

   i) To provide funds to establish an Industrial Fellowship program that would enable local industry to attract outstanding scientists on a visiting basis. The term of such visits could vary from one week to as long as one year.

   ii) To provide funds to attract outstanding scientists to British Columbia universities on a visiting basis. It is anticipated that the term of such visits would vary from one week to as much as one year.

2. To enhance the coordination of the activities of members of the Institute and to facilitate collaboration and cooperation between the members, the Institute will sponsor the following:

   (a) Special Projects

   To provide funds to support special joint university-industry research projects which must be initiated quickly and have the potential to produce significant new results. Funds would also be used for urgent equipment requirements, special travel needs, and for start-up funding for successful URF candidates.

   (b) Literature Database Facility

   To provide support for the establishment and maintenance of a database of publications and reports that are issued in preprint form.

   (c) Conferences

   The Institute would assist in the organization and sponsorship of local conferences on a regular basis.

   These conferences would involve foreign scientists as well as those in British Columbia who are involved in research in high-T_c superconductivity.

3. To enhance the public awareness of the potential applications and economic benefits of high-T_c superconductivity, the Institute will sponsor:

   (a) Short Courses

   Such courses would be directed to government personnel and people in local industry. The courses might be a few hours in length and would be presented at a level suitable for the layman.

   (b) Public Lectures

   Such lectures would be presented by visiting scientists as well as individuals from local industry, government and the British Columbia universities.

4. Administration.

Some administrative costs will be incurred in coordinating and publicizing the activities of the Institute. To keep these costs to a minimum, it is suggested that a member of the Institute assume the Directorship. This person would be appointed by the Board of Trustees. Funds would be required to provide teaching relief and a salary stipend if the Director was a University Faculty Member or for salary compensation if the Director was chosen from local industry. Funds would also be required for secretarial support, for a small operating budget, and for the establishment of a Scientific Advisory Board. These administrative services could be provided under contract by the Science Council of B.C. in the same way it does for the Advanced Systems Institute.

APPENDIX A

SUPERCONDUCTING ELECTRONICS: CURRENT STATUS AND FUTURE PROSPECTS

APPENDIX A

Superconducting electronics: current status and future prospects

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Superconducting electronics can provide devices and circuits with properties not obtainable for any other known technology; i.e. very low loss, zero frequency-dispersion signal transmission lines, very high Q-value resonators and filters, and quantum limited electromagnetic sensors for radiation from d.c. through the millimetre wave region and into the infrared. The impact of the newly discovered high temperature superconducting materials with transition temperatures in excess of 90 K could revolutionize electronic technology as it would bring these very interesting properties and device behaviour to an operating temperature where: 1, refrigeration requirements are greatly reduced; and 2, where hybrid semiconductor-superconductor circuits can be built which make use of the best features of each technology. In addition, new phenomena might be discovered in these new materials which could impact electronic technology.

Keywords: superconductivity; superconducting electronics; high temperature superconductivity; critical current density; critical magnetic field

Superconductivity, due to its quantum mechanical nature, can provide the ultimate in electronic device and circuit technology[1-6]. Superconductivity can provide very low loss, zero frequency-dispersion signal transmission lines and passive circuit components, while electromagnetic sensors and digital gates can have characteristics limited by the Heisenberg Uncertainty Principle. There is no other known electronic technology that can provide any of these features, let alone all of them.

Prior to December 1986, all known superconductors exhibited transition temperatures (T_c) below 23 K. These very low temperatures required the use of liquid helium, which is expensive, or the use of energy intensive closed cycle refrigeration systems. Thus, superconductivity remained in the laboratory or was used only in very special situations, such as radio astronomy, where the ultimate in performance was required and where cost was not an issue.

The recent breakthrough in superconducting materials has resulted in materials with transition temperatures as high as ≈ 100 K with, as yet, unsubstantiated reports of still higher transition temperatures. These materials, when suitably fabricated into useful conductors or electronic devices and circuits, will be capable of operation in temperature ranges around 77 K. Providing cryogenic environments in this temperature region can be achieved using liquid nitrogen, which is relatively inexpensive – a litre of nitrogen costs less than a litre of milk – or with the use of very small, lightweight and inexpensive closed cycle coolers. Thus, superconductivity may now move out of the laboratory and become commercially feasible.

Background

Superconductivity is a quantum mechanical phenomena[7,8] that is found in many elements, compounds and alloys when they are cooled to cryogenic temperatures. In 1911, superconductivity was discovered in mercury at a temperature of 4.2 K[9]. Over the next 75 years, additional superconducting materials were discovered with ever increasing transition temperatures. In 1973, the compound Nb_3Ge was discovered to be superconducting with a transition temperature of 23 K. Over this span of time, the highest known transition temperature increased at a rate of ≈ 0.3 K per year (see *Figure 1*). Nb_3Ge held the record for the highest known T_c until the end of 1986. At that time, the compound La–Ba–Cu–O was prepared in single phase form and was found to have a T_c value near 30 K[10,11]. Within the next three *months* other ceramic copper oxide compounds were studied and T_c values as high as 100 K were reported. During this period of time, the rate of increase of T_c was of the order of 0.3 K per day, a rate about 1000 times greater than that prior to December 1986. This spectacular rate of increase in T_c and the occurrence of superconductivity at liquid nitrogen temperatures has initiated a revolution in how the engineer, scientist and the layman think about superconductivity. More will be said about these spectacular results and their impact on electronic technology below.

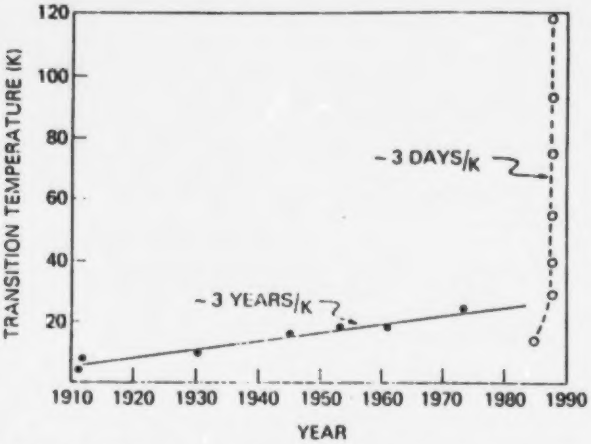

Figure 1 Highest known superconducting transition temperature as a function of time. ●, ——·—, Data for elemental, alloy and compound superconductors; ○, --, oxide superconductors

The superconducting state has very interesting properties that can result in electrical and electronic devices and components with unique characteristics. The best known property, which resulted in the use of the term 'superconductivity' to describe this phenomena, is that of zero electrical resistance. When superconductive materials are cooled to temperatures below their transition temperatures, the specimens have zero electrical resistance, that is, d.c. electric current can flow without heat dissipation. If an electrical current is induced in an all superconducting circuit, it will continue to flow indefinitely. If the current does decrease, it has been estimated that it would take more than 10 000 000 years before the magnitude of the current dropped to 23% of the original value; provided, of course, that the sample is continuously maintained below its T_c. The electrical resistance of a superconductor at low frequencies is more than 16 orders of magnitude smaller than that of high purity copper at room temperature.

A second property of a superconductor is magnetic flux exclusion. If a superconductive specimen at a temperature above T_c is exposed to a magnetic field, when the sample is cooled through its transition temperature, the magnetic field is expelled from the interior of the specimen[12] (see *Figure 2*). (Strictly speaking, the magnetic field is expelled from the interior of the specimen, but does penetrate slightly into the specimen to a depth of the order of a fraction of a micrometre.) If the specimen is in the form of a hollow cylinder or washer-shaped ring, the field is expelled from both the inner and outer surface of the specimen (see left and centre portions of *Figure 2*). The magnetic field trapped in the bore of the sample has discrete values which are multiples of a quantity known as the magnetic flux quantum divided by the area of the hole in the specimen[13,14]. The magnetic flux quantum is equal to the ratio of the two fundamental physical quantities, Planck's constant, h, divided by twice the charge on the electron, $2e$. This quantum of magnetic flux has the value of 2.07×10^{-15} weber, Wb (2.07×10^{-7} gauss centimetre^2, G cm^2). For example, if the bore has an area of 1 cm^2, the trapped magnetic field will be multiples of 2.07×10^{-11} T (2.07×10^{-7} G), which is a very small value of magnetic field. The quantization of magnetic flux can be used to create magnetic shields to provide stable magnetic field environ-ments and for EMI protection. With the sample at temperatures below T_c, if the applied magnetic field is removed, the quantized magnetic flux through the ring will remain trapped and thus the magnetic flux lines will be as shown in the right hand portion of *Figure 2*, resulting in a circulating current being induced to flow in the ring. As long as the ring is maintained at temperatures below T_c, this current will be 'persistent' and not diminish in magnitude as a function of time.

A third property of the superconducting state which can impact on its potential electronic applications is associated with the current flowing across a structural inhomogeneity consisting of two superconducting regions separated by a thin barrier layer (see, for example, chapter 2 of Reference 1 and chapter 1 of Reference 2). This superconductor–insulator–superconductor (SIS) structure is commonly known as a Josephson tunnel junction or an SIS device. As the temperature of the superconductor is lowered through its transition temperature, the electron energy states at the Fermi level are split into two bands: the states below the Fermi level are associated with the bound Cooper pairs, which can move through the specimen with no electrical resistance while the electron states above the Fermi level are associated with normal (dissipative) electrons. As the temperature is lowered below the transition temperature, this energy gap, the spacing between the top of the energy states for the Cooper pairs and the bottom of the band for normal electrons, will gradually open with decreasing temperature. At the absolute zero of temperature, the energy gap has achieved its maximum value and is roughly proportional to its superconducting transition temperature. In *Table 1*, the relation between transition temperature and energy gap, expressed in terms of voltage and frequency, is shown. The semiconductor-style energy band diagrams for an SIS structure as a function of applied bias are shown in the left hand portions of *Figure 3*. As a bias voltage is applied to the SIS structure, the bands begin to be offset. As long as the filled states near the top of the energy band associated with the Cooper pairs are opposite to the energy gap in the other electrode (where there are no electron energy states of any kind), no current can flow. However, once the top of the filled Cooper band is opposite to the bottom of the normal electron band (see lower left hand portion of *Figure 3*), Cooper pairs

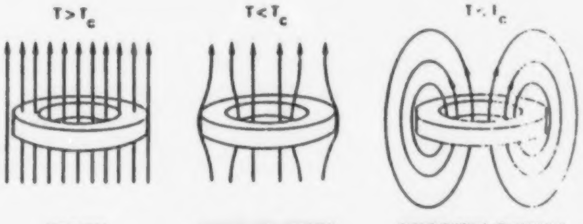

Figure 2 Magnetic flux expulsion from a superconducting ring cooled in a constant magnetic field. The left hand figure illustrates the magnetic flux threading the ring when the temperature is above the superconducting transition temperature, while the centre trace illustrates the magnetic flux line profile when the temperature is below the transition temperature of the ring. The right hand trace illustrates the flux line configuration when the magnetic field has been removed with the sample still in the superconducting state

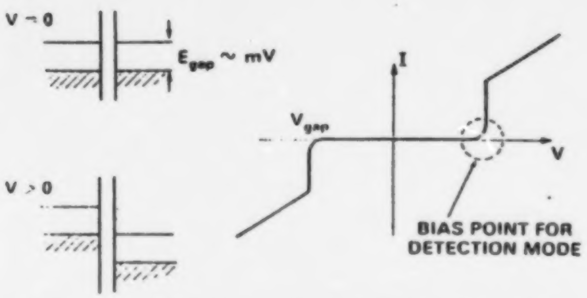

Figure 3 Energy band diagram for superconducting tunnel junction for zero applied bias (upper left hand trace) and for finite bias (lower left hand trace), and current *versus* voltage characteristic for superconducting tunnel junction device

will tunnel across the barrier region and will break up into two normal electrons, resulting in a normal (dissipative) current flow across the device. As this bias condition is exceeded, there will be an abrupt increase in current flow. The current *versus* voltage characteristic for such a device is shown in the right hand side of *Figure 3*. Note the very abrupt increase of current at the gap voltage, E_g. This very sharp non-linearity in the I–V curve of an SIS structure is used to detect microwave and millimetre wave radiation with very high efficiency (see below).

The typical superconductor–barrier–superconductor structure can be fabricated with a variety of different barrier systems: an (insulating) oxide barrier of 1 to 2 nm in thickness; a high resistance semiconductor barrier of thickness 5–10 nm; and normal metal barriers of thickness 100–500 nm. These structures are commonly known as Josephson junctions, after Brian Josephson who first theoretically described supercurrent flow across an insulating barrier separating two superconducting regions[13]. There is another class of structures which show many of the phenomena associated with Josephson junctions. This is illustrated in *Figure 4*. If a superconducting specimen, for example, a thin film, has its lateral dimensions drastically reduced at one point along its length and a current is induced, as the magnitude of the current is increased, the current density through the constriction (or 'weak link') will exceed the critical current density (see below) of the material, and a small region of the weak link will be driven into the normal state, thus dynamically decoupling the two massive regions (or 'banks') on opposite ends of the weak link. Other weak link structures include a sharply pointed superconducting wire making contact with a superconducting anvil or a normal metal deposited over a narrow region of the superconductor which will suppress the T_c in the region below the overlay (the proximity effect). For those superconducting material systems for which T_c is a function of film thickness, the T_c of a local region can be depressed either by shallow implantation of ions which destroy superconductivity or by reducing the film thickness. This illustrates only some of the superconducting structures which can exhibit Josephson phenomena.

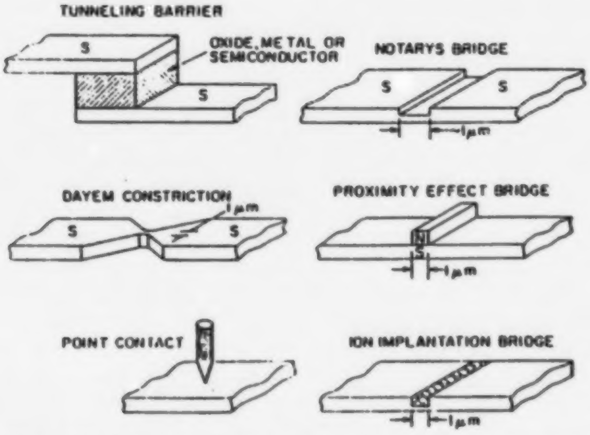

Figure 4 Schematic drawing of several superconducting structures which exhibit Josephson behaviour

For completeness, two other concepts about the superconducting state will be mentioned. The critical magnetic field is the largest magnetic field to which a superconductor can be exposed and still remain in the superconducting state. The critical magnetic field, like the critical temperature, is an intrinsic property of the particular superconductor. In *Figure 5*, the critical magnetic field is shown as a function of temperature for a number of low temperature superconductors. Note that the shapes of these curves are similar and that as T_c increases, the value of the magnetic field at temperatures approaching absolute zero also increases. Assuming this general scaling between T_c and critical field, the new ceramic oxide superconductors, which have T_c near 100 K, should have a value for the critical magnetic field in excess of ≈ 200 T (2 MG)!

Another parameter of the superconducting state which is of interest for applications is the critical current density which is the largest current density that a superconducting specimen can support while remaining in the superconducting (zero dissipation) state. The critical current density is an extrinsic property and depends very strongly on the processing and past history of the specimen. Values of critical current density for a suitably prepared sample at temperatures well below T_c range from 10^6 to

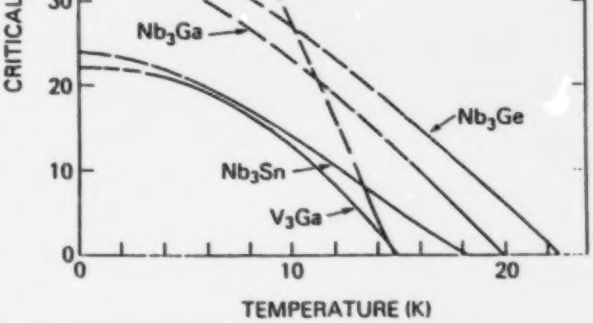

Figure 5 Plot of critical magnetic field as a function of temperature for several superconducting materials

10^7 A cm^{-2}. (As the temperature is raised toward T_c, the maximum current density decreases, becoming zero at T_c.) The value of current density required for any particular application will depend on the applications; it may approach the critical value or it may be smaller.

Electronic applications

Low loss signal transmission lines

The zero resistance property of superconductivity has many applications in electrical and electronic technologies. Its most common use has been in the form of conductors (wires, cables and tapes) which have been used to build magnets for applications such as nuclear particle accelerators, magnetic resonance imaging (MRI) for medical diagnosis, and for very intense research magnets. In low power electronic applications, this property of superconductivity can provide passive circuit components with very impressive characteristics. In *Figure 6*, the surface resistance of a normal-metal conductor at 300 and 4 K and a superconductor (lead) at a temperature above its transition temperature are shown, along with the intrinsic electrical losses of a superconductor at several values of reduced temperature, i.e. the ratio of the operating temperature to the transition temperature[16]. Normal conductor losses vary as the square root of the frequency, while the surface resistance of a superconductor varies as the square of the frequency. In addition, the magnitude of the surface losses for a superconductor varies exponentially with the reduced temperature. It can be seen that for a superconductor operating at a reduced temperature of ≈ 0.55 (i.e. lead with a $T_c = 7$ K operating at 4 K or Y–Ba–Cu–O which has a $T_c = 90$ K operating at 50 K), the surface loss at 1 GHz is smaller by five orders of magnitude than copper at room temperature, while at 100 GHz, the advantage is only about a factor of 30. At a reduced temperature of 0.12 (that is, operating a 90 K superconductor at 10 K), the losses for a superconductor compared to that of copper at room temperature are more than six orders of magnitude smaller at 1 GHz and about four orders of magnitude smaller at 100 GHz.

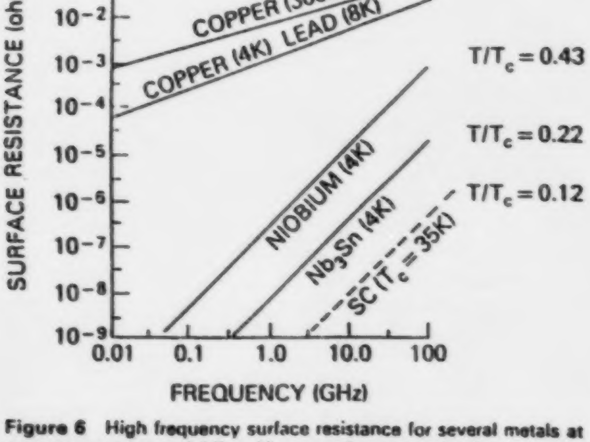

Figure 6 High frequency surface resistance for several metals at room temperature and 4 K and for several superconducting materials at 4 K

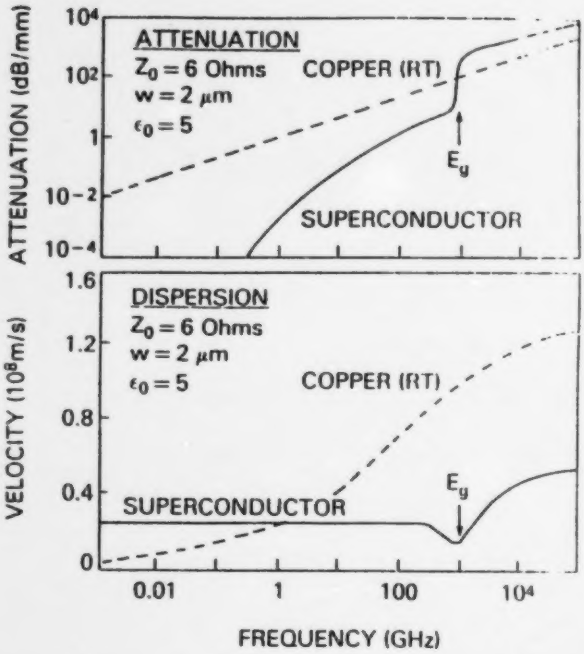

Figure 7 Attenuation and dispersion *versus* frequency for microstrip lines fabricated with superconducting lead and with room temperature copper

Using superconductors for microwave filters and resonant circuits, Q-values of $> 10^6$–10^9 can be achieved. The very low loss property of a superconductor can be used to build staggered tuned multiple filters with very steep frequency roll-off characteristics and very high out of band isolation.

This low loss property can also be used to build microwave frequency striplines with very interesting properties, as shown in *Figure 7*. This figure illustrates the attenuation and phase velocity for striplines fabricated from copper and from a superconductor operating at a reduced temperature of 0.55 (References 17 and 18). The upper curve shows that the attenuation for superconductor striplines is orders of magnitude smaller than for the copper lines for all frequencies below the frequency corresponding to the energy gap, E_g. The phase velocity is constant, independent of frequency from very low frequencies up to about one-third or one-half of the gap frequency. Thus, superconducting striplines can transmit pulses with very low attenuation and no dispersion for pulses with frequency components below about one-third or one-half of the gap frequency. Thus, not only does the signal amplitude not diminish after propagating along a superconducting stripline, but all of the frequency components will travel with the same velocity and, hence, there is very little spreading or 'smearing' of the signal. These properties of superconducting passive components have very important implications in both high frequency analog signals and high speed digital interconnects.

High frequency detection

The very sharp non-linearity of the current *versus* voltage curve of an SIS tunnel device (such as that illustrated in *Figure 3*) can be used for quantum limited detection of

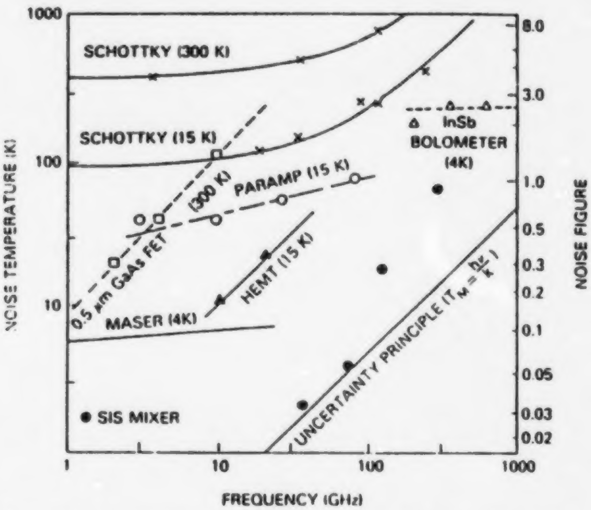

Figure 8 Comparison of noise characteristics of various mixer technologies at room temperature and cryogenic temperatures

microwave and millimetre wave radiation[19]. This is illustrated in *Figure 8*, where the noise temperature (left hand scale) and the noise figure (right hand scale) for a number of detector technologies are plotted as a function of signal frequency[20]. In the 1–10 GHz region, field effect transistors (FET's) with gate lengths of the order of 0.5–0.25 μm can provide very low noise amplifiers. With increasing signal frequency, the noise increases with the frequency, and at frequencies greater than 30 or 50 GHz, all conventional devices, both room temperature and cryogenically cooled, exhibit performances which degrade more rapidly than if proportional to increasing frequency. At frequencies up to ≈100 GHz, superconducting SIS mixers have demonstrated, to within a factor of two, quantum limited detection, i.e. for each incident microwave or millimetre wave photon, one electron is generated in the external circuit in which the mixer is embedded. No conventional technology can approach quantum-limited operation throughout the frequency band from 10 to 1000 GHz. Since the SIS mixer process is quantum-mechanical in nature, under suitable conditions (that is, proper impedance matching at the relevant frequencies), these devices can exhibit conversion gain, a property not found in any other mixer technology. If the mixer has conversion gain, the influence of the IF amplifer on the overall receiver noise temperature is diminished. Receivers at 36 and 94 GHz have been built with superconducting mixers operated such that they show conversion gain and have demonstrated receiver noise temperatures of 24 K or less[21,22]. These are the lowest noise temperatures reported for any millimetre wave receiver technology. It is anticipated that this level of performance – close to the quantum limited mode – should be achievable well above 100 GHz up to about one-half the gap frequency from which the mixers are fabricated (see *Table 1*).

Digital logic and memory device technology

Superconducting tunnel devices can be operated as very fast gates, by switching from the superconducting to the normal state. The speed–power figure of merit for several technologies is shown in *Figure 9*[23]. Superconducting gates and high electron mobility transistors (HEMT) can switch in times ≈10 ps. However, the power dissipation for the superconducting device is two to three orders of magnitude smaller than for the HEMT. Thus, higher packing densities should be achievable with Josephson gates. The ultimate switching time for the HEMT device depends on the transit time for electrons between the source and the drain. Thus very small dimensions, of the order of 0.25 μm, were used to achieve these very fast switching times. The minimum feature size for the Josephson devices shown was only 2.5 μm. Thus, Josephson technology can be extended to still shorter switching times before the limits of fabrication will become an obstacle. In principle since the operation of the Josephson device is based on quantum mechanical tunneling, the ultimate limitation on switching time should be given by the Heisenberg Principle which, for a material with a transition temperature of 10 K, would be ≈0.1 ps, while, for a 100 K material, the limiting switching time should approach 0.01 ps. To fabricate an FET with comparable switching times would require feature sizes of the order of 2.5–5 nm or about five lattice spacings – a very demanding requirement for current device lithography. Thus, superconducting digital gates should approach quantum limited operation within the domain of the present status of device processing.

Superconducting digital applications include logic and memory devices for high speed, high throughput digital computers and analog-to-digital converters for signal

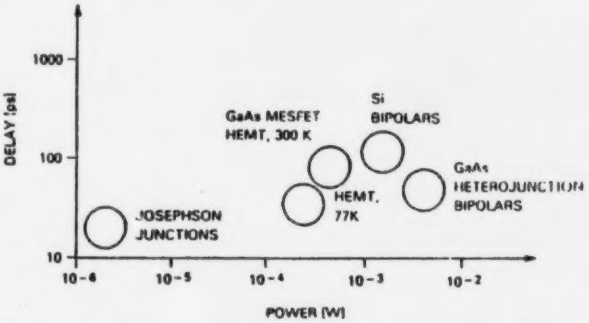

Figure 9 Comparison of gate delay–power dissipation characteristics for several digital technologies

Table 1 Comparison of transition temperatures of a superconductor with the energy gap expressed in millivolts and frequency

Transition Temperature (K)	1	10	15	30	90	120
Energy Gap (mV)	0.3	4.3	8.6	8.6	26	35
(THz)	0.068 (68 GHz)	1.03	2.1	4.1	12.3	16.4

processing applications. The development of a superconducting digital computer was pursued by IBM (see, for example, Reference 24) for a number of years until 1983 when it was terminated. A Japanese activity to develop a superconducting digital computer continues. IBM was successful in developing logic circuits, interconnect wiring and input–output lines, while they encountered problems in attempting to build memory chips with densities of 1000 or more cells per chip. These memory cells employ Josephson junctions which are two terminal devices, which place very stringent tolerances on the fabrication technology for uniformity of device characteristics across a chip and from chip to chip. The fabrication process developed by IBM was not adequate to produce memory chips with densities greater than 1 kbit with an acceptable yield. The Japanese programme which has continued after the termination of the IBM project, has not yet reported a fully operational 1 kbit memory chip. There are at least three alternative approaches for fabricating memory chips with density greater than 1 kbit: 1, develop an integrated circuit technology with much closer parameter tolerances; 2, develop memory circuit concepts which are compatible with the presently available device tolerances that would result in high density memory chips; and 3, develop a three terminal device similar to the semiconductor FET which has both current and power gain and, thus, does not demand fabrication tolerances as stringent as those required for Josephson digital memory technology. All three approaches are being pursued by various research organizations but no breakthrough has been reported to date.

Magnetic field sensors

The electrical impedance of a circuit containing SIS devices, in an otherwise totally superconducting circuit, is very sensitive to applied low frequency magnetic fields. These circuits are commonly known as superconducting quantum interference devices or SQUIDs[25,26]. The magnetic field sensitivities of various magnetometer technologies are shown in *Figure 10*. The performance achieved for the best SQUID magnetometer in the high frequency 'white noise' region is within a factor of 2 of the value corresponding to an energy change of the order of Planck's constant – the quantum of energy[27]. All competing technologies have magnetic field instrument noise levels three to four orders of magnitude above this ultimate quantum limit. (The source of the low frequency magnetic field noise in SQUID sensors which varies inversely with the square root of frequency, is not understood at the present time.) Superconducting magnetometers have found widespread use in the form of ultrasensitive laboratory measurement instrumentation and for magnetic field geophysical exploration and in biomagnetic studies of the human body.

Thin film integrated circuit technology

A sophisticated thin film circuit technology is required to fabricate the sensors, devices and circuits described above, with the 'weak link' sensors the simplest and the digital memory chips probably the most complex. A digital chip may have eight to 10 layers of superconducting metallization layers, resistors, insulators, etc. and from 15 to 20 processing steps[24]. However, space does not permit detailed descriptions of the fabrication technology necessary for each type of device or circuit. To illustrate what contributes to superconducting integrated circuit (IC) technology, *Table 2* contains a list of some of these components with some of the critical properties or characteristics that must be determined. The magnitudes of those properties marked with an asterisk must be measured with some precision as their values are crucial in the design of superconducting devices or circuits.

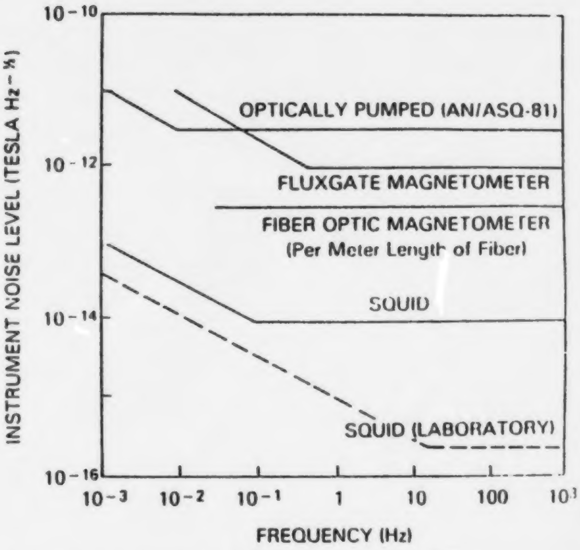

Figure 10 Comparison of magnetic field sensitivities *versus* signal frequency for several magnetometer technologies

The development of high T_c superconducting devices and IC technologies will present very severe challenges to scientists and technologists. The high transition temperature of the $Y_1Ba_2Cu_3O_{7-x}$ material depends very crucially on crystal structure and stoichiometry, with the oxygen concentration an extremely critical factor. Experimentally, it has been observed that the oxygen can move in and out of the open perovskite crystal structure easily, even at modestly low temperatures such as 400°C. In addition, the high processing temperature of ≈900°C required to order the anions and to introduce the optimal concentration of oxygen into the structure, may have deleterious effects on previously processed layers in a multilayered IC structure. Furthermore, the chemical reactivity of the 1–2–3 compounds to air and to CO_2 will probably require compatible passivation layers to protect the completed structures and will make the problem of very low resistance contacts to these materials extremely difficult. However, the advantages that can be realized from superconducting electronics operating at temperatures in the vicinity of liquid nitrogen are so attractive (see below), a major research and development effort to solve the chemical and physical problem areas associated with these high temperature superconducting materials is certainly warranted.

Refrigeration

The properties of the superconducting state were known before December 1986. A variety of sensors, devices and

Table 2 Properties of several components of a superconducting thin film integrated circuit

Thin film technology

• Appropriate crystal structure and stoichiometry
• Transition temperature
Substrate material
Good adhesion
Non-interactive
Epitaxial growth
• Critical current density ($J_c \sim 10^5$ A cm^{-2})
• Energy gap voltage
• Penetration length
Coherence length
Chemical and thermal stability

Tunneling junctions technology

Types of tunneling barriers
Native oxides
Artificial oxides
Semiconducting materials
Semi-metals
Metals

Properties
Controllability of critical current
• Critical current density
• Low subgap leakage (V_m figure of merit)
• Specific capacitance
Does not react chemically with electrode materials
Withstands IC processing temperatures

Insulating layers

Pinhole-free
• Low high frequency electrical losses
Good step-edge coverage
Deposition and temperature processing parameters compatible with superconducting materials

Resistor technology

• Specific resistivity

'Zero' resistance electrical contact technology

• Superconductor-to-superconductor
• Superconductor-to-resistor
• Superconductor-to-chip pin out pads

*Magnitudes of those parameters marked with an asterisk are crucial in the design of superconducting devices and chips

circuits had been fabricated using the 'low' temperature superconductors then known, i.e. those with T_c of <23 K. One of the primary obstacles to the wide spread use of superconducting electronic technology based on these low T_c materials was the expensive cryogenic refrigeration systems that are required to cool these materials. *Table 3* lists some of the properties of liquid cryogens and cryogenic refrigeration systems required to provide temperatures in the 4–77 K range. The properties of a superconductor are temperature independent at temperatures well below T_c but begin to change as the temperature is raised (see *Figure 11*). At about half of T_c, the parameters of the superconductor are close to their $T = 0$ K values. At about two-thirds of T_c, the parameters have decreased slightly. At still higher temperatures, approaching the transition temperature, the parameters change rapidly with temperature. Hence one would prefer to operate superconductors at temperatures near or below half of T_c but devices could also operate up to about two-thirds of T_c before the strong temperature dependence would require rather stringent temperature control for the cryogenic environment. The third column of *Table 3* shows the values of T_c for which the indicated bath temperature would be about two-thirds of T_c. Thus, liquid helium is a suitable bath for superconductors with T_c of 6 K or more, liquid hydrogen for materials with T_c of 30 K or higher, while liquid nitrogen would provide a suitable cryogenic environment for superconductors with $T_c > \approx 120$ K. The fourth column shows the relative heat of vaporization for the various cryogens. Note that the heat of vaporization of nitrogen is ≈ 60 times greater than that of liquid helium. That is to say, for a given open cycle dewar system, if 1 dm^3 of liquid helium lasts for one day, then 1 dm^3 of liquid nitrogen would last for about 60 days. These extended hold times for a nitrogen dewar relative to a helium dewar greatly relax the logistic requirements for replenishing the required liquid cryogens. Furthermore, there would be a large saving in cost: a litre of liquid helium costs between \$5 and \$10, while a litre of liquid nitrogen costs only about \$0.25. Hence, the combined greater heat of vaporization and the lower price of nitrogen results in a reduction by a factor of ≈ 1200 in the daily cost of providing the required environment for a superconducting device or system operating near 77 K, compared to one operating at 4 K.

The cryogenic environment required for a superconducting device can also be provided by closed-cycle cryogenic refrigeration systems ('cryocoolers'). According to Carnot's Law, a cryocooler requires more input power at the high (heat rejection) temperature, the lower the cold temperature. In the fifth column of *Table 3*, the relative coefficient of performance, the inverse of the ideal Carnot efficiency, is shown. An ideal cryocooler providing a given amount of cooling at 77 K would require 24 times less input power than would be required to provide the same amount of cooling at 4 K. The last column of the table presents typical values of input power at room temperature required to produce 1 W of cooling at the indicated temperature. A 4 K cryocooler requires about 1000 W of input power for each watt of cooling at 4 K, while a 77 K cryocooler requires between 30 and 40 W per watt of cooling at 77 K.

Another parameter which is crucial in understanding the cryogenic cooling of electronic devices and circuits is the amount of heat that can flow across a surface from a chip into the cryogenic bath. This is illustrated schematically in *Figure 12*, where the heat flux across a surface into a liquid nitrogen bath is plotted as a function of temperature difference between the specimen and bath. The temperature difference increases roughly as the square root of the heat flux up to the peak nucleate boiling point, where bubbles begin to form at the surface, interfering with heat transfer. The peak nucleate boiling heat flux across a solid–liquid interface as a function of temperature is shown in *Figure 13* for several cryogenic liquids at a pressure of 1 atm*. Also shown in this figure is the heat flux across the solid–liquid interface for a 5% temperature difference. Note that the slope of both these curves is unity, indicating that the heat flux for both situations

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*1 atm = 101 kPa

Table 3 Cryogenic refrigeration considerations

	Liquid Cryogen		Cryocoolers		
Gas	Boiling point (K)	$T_c \geq \frac{3}{2} T_{op}$ (K)	Relative heat of vaporization	Relative coefficient of performance	W/W
Helium	4.2	6	1	1	1000
Hydrogen	20.4	30	11.6	5.1	195
Neon	27.1	41	38.5	7.0	143
Nitrogen	77	116	58.4	24.3	42

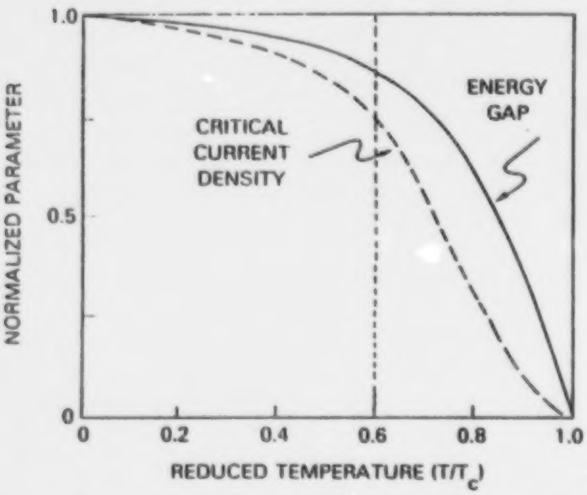

Figure 11 Schematic variation of critical current density and energy gap of a typical superconductor as a function of reduced temperature (T/T_c)

increases linearly with bath temperature. Thus, not only is refrigeration at 77 K much more energy efficient than at 4 K, but the heat flux across a solid–liquid interface increases by a factor proportional to the temperatures and thus there is more efficient cooling of chips at the higher temperatures.

Hybrid semiconductor–superconductor technology

The advent of superconductivity at temperatures near 77 K raises the possibility of hybrid semiconductor–superconductor devices and circuits[28,29]. The possibility was not readily realized for low temperature superconductivity, as many semiconductor devices at temperatures near 10 K experience 'freeze-out', i.e. the electrons thermally excited from the donor levels in an n-type semiconductor at higher temperatures do not have enough thermal energy to remain in the conduction band and are trapped back on the donor levels. Without conduction electrons, the semiconductor device cannot function. However, at temperatures above ≈30 K, the donors are ionized providing electrons in the conduction band. This is illustrated in *Figure 14*, where the conductivity of lightly and heavily doped semiconductors is shown as a function of temperature.

Another desirable feature of semiconductors at cryogenic temperatures is that the carrier mobilities increase with decreasing temperature below room temperature, and many exhibit maximum mobility values at temperatures near or slightly below 77 K. This is shown in *Figure 15*, where mobility as a function of temperature is shown for germanium, silicon and gallium arsenide. Another advantage of operating semiconductors at cryogenic temperatures is that the thermal conductivity of semiconductors tends to have a maximum at temperatures between 20 and 50 K. This would enhance the heat removal from the active regions of the device to the substrate.

Operating semiconductors at temperatures near and below 77 K can lead to an increase in device reliability. Many mechanisms responsible for the degradation of electronic devices, such as electromigration of materials in the interconnects are thermally activated, and lowering the operating temperature of a semiconductor device from 85°C (i.e. 'room temperature' for typical devices) to 77 K will slow down thermally activated processes by about four to five orders of magnitude.

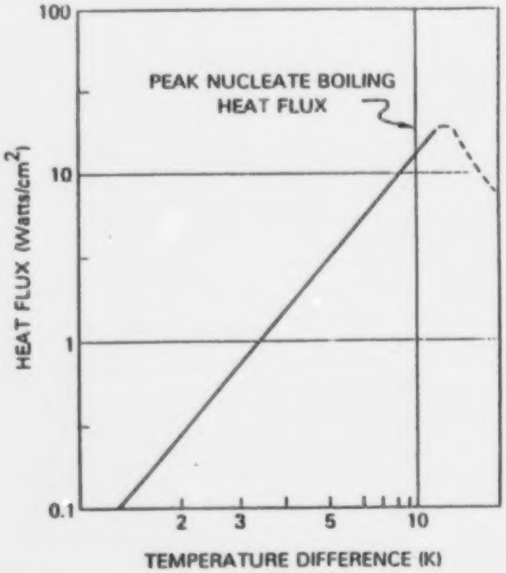

Figure 12 Heat flux across a solid interface into liquid nitrogen at 1 atm pressure as a function of temperature difference across interface

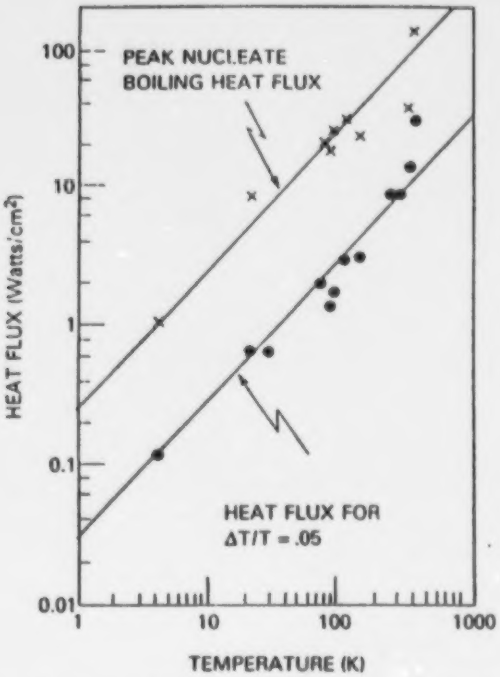

Figure 13 Peak nucleate boiling heat flux at a solid-liquid interface as function of temperature for boiling liquid at 1 atm pressure and heat flux across interface for a temperature difference of $\Delta T/T = 0.05$

The integration of low loss, zero frequency-dispersion signal transmission lines fabricated from superconducting materials with transition temperatures above 77 K with semiconductor devices and circuits can have a great impact on high performance chips and systems. This hybrid configuration of superconducting signal transmission lines and cryogenically cooled semiconductor devices and circuits would exploit the most desirable features of each technology.

A hybrid semiconductor–superconductor technology, can not only exploit the best features of each of the individual technologies, but could lead to novel device concepts, such as new three terminal device structures, or, possibly, totally new device and circuit concepts. It should be noted that the invention of the transistor did not immediately revolutionize the electronics industry. However, the transistor did lead to the invention of the integrated circuit which did revolutionize the electronics industry. Maybe the advent of high temperature superconductivity and the hybridization of high temperature superconductivity and cryogenically cooled semiconductors may result in the next 'integrated circuit' to impact electronic technology.

Summary

Superconductivity can provide electronic sensors with ultimate sensitivities limited by the Uncertainty Principle. Furthermore, the low electrical losses in superconductors can be used for very low loss, zero frequency-dispersion signal transmission lines or interconnects, for low loss microwave and millimetre wave control components and for very high Q-value filters and resonators. No other electronic technology can provide comparable characteristics.

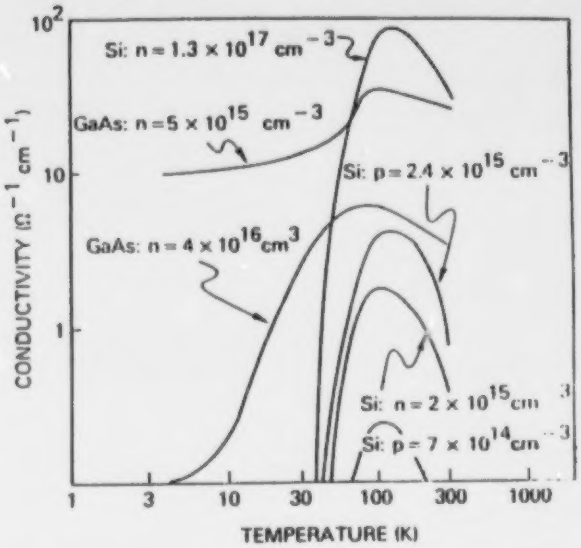

Figure 14 Schematic plot of conductivity *versus* temperature for several semiconductor materials

The development of a viable superconducting IC technology requires several crucial components, including superconducting metallization layers, superconducting tunneling device structures, insulating layers, resistors and 'zero' resistance electrical contacts between these components. Concurrent with the development of

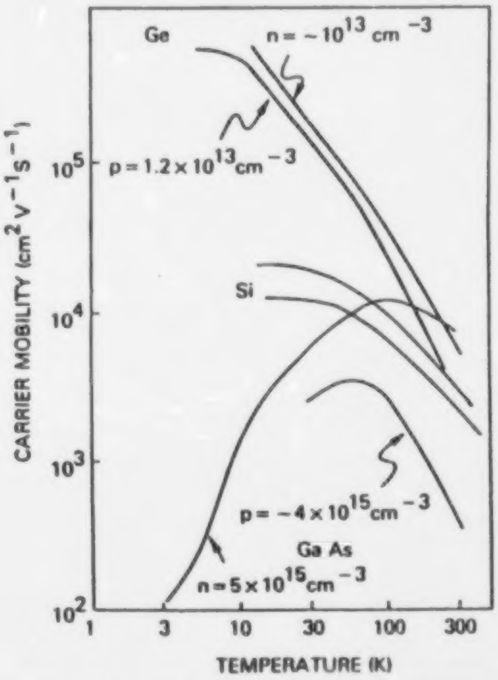

Figure 15 Carrier mobility as a function of temperature for several semiconductor materials

such a technology, detailed performance trade-offs against existing technologies (taking into account weight, volume, input power, cost and refrigeration) must be performed to determine the projected enhancement in performance to be realized from the use of superconducting technology.

The advent of the recently discovered high temperature superconducting materials with transition temperatures above 77 K will expedite the introduction of superconductivity into widespread use. The elevated operating temperatures for the new materials will allow much less complex and more energy efficient cryogenic refrigeration systems. In addition, these high temperature superconducting materials will permit hybrid semiconductor–superconductor circuits and systems which can take advantage of the best features, both technical and economical, of each technology. Thus, the advent of high temperature superconductivity may have a revolutionary impact on all areas of high performance electronic technology.

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APPENDIX B

SUPERCONDUCTORS!

THE STARTLING BREAKTHROUGH THAT COULD CHANGE OUR WORLD

TIME MAGAZINE; MAY 11, 1987

APPENDIX B

COVER STORY

Superconductors!

The startling breakthrough that could change our world

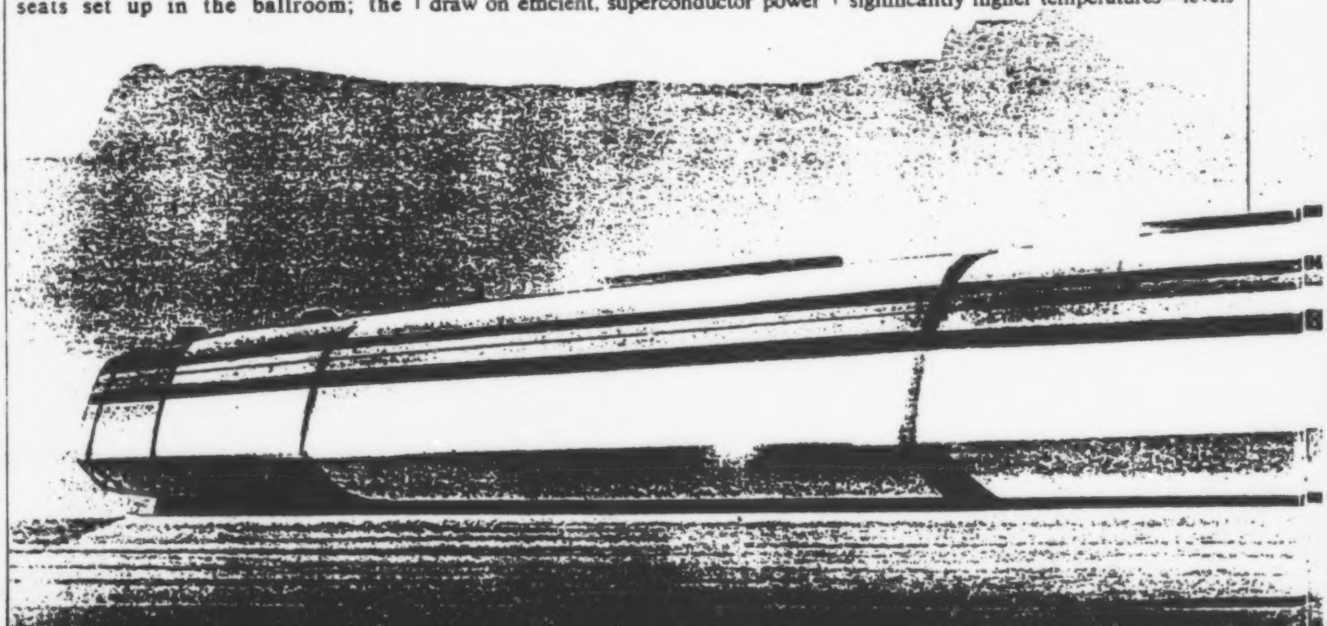
They began lining up outside the New York Hilton's Sutton Ballroom at 5:30 in the afternoon; by the time the doors opened at 6:45, recalls Physicist Randy Simon, a member of TRW's Space and Technology Group, "it was a little bit frightening. There was a surge forward, and I was in front. I walked into the room, but it wasn't under my own power." Recalls Stanford Physicist William Little: "I've never seen anything like it. Physicists are a fairly quiet lot, so to see them elbowing and fighting each other to get into the room was truly remarkable."

Thus began a session of the American Physical Society's annual meeting that was so turbulent, so emotional and so joyous that the prestigious journal *Science* felt compelled to describe it as a "happening." AT&T Bell Laboratories Physicist Michael Schluter went even further, calling it the "Woodstock of physics." Indeed, at times it resembled a rock concert more than a scientific conference. Three thousand physicists tried to jam themselves into less than half that number of seats set up in the ballroom; the rest either watched from outside on television monitors or, to the dismay of the local fire marshal, crowded the aisles. For nearly eight hours, until after 3 a.m., the assembled scientists listened intently to one five-minute presentation after another, often cheering the speakers enthusiastically. Many lingered until dawn, eagerly discussing what they had heard and seen.

What stirred all the excitement at that tumultuous meeting in March was a discovery that could change the world, a startling breakthrough in achieving an esoteric phenomenon long relegated to the backwaters of science: superconductivity. That discovery, most scientists believe, could lead to incredible savings in energy; trains that speed across the countryside at hundreds of miles per hour on a cushion of magnetism; practical electric cars; powerful, yet smaller computers and particle accelerators; safer reactors operating on nuclear fusion rather than fission and a host of other rewards still undreamed of. There might even be benefits for the Strategic Defense Initiative, which could draw on efficient, superconductor power sources for its space-based weapons.

Superconductivity is aptly named. It involves a remarkable transition that occurs in many metals when they are cooled to temperatures within several degrees of absolute zero, or, as scientists prefer to designate it, 0 Kelvin. Absolute zero, equivalent to −460° F or −273° C, represents a total absence of heat; it is the coldest temperature conceivable. As the metals approach this frigid limit, they suddenly lose all their electrical resistance and become superconductors. This enables them to carry currents without the loss of any energy and in some cases to generate immensely powerful magnetic fields. Scientists have recognized for years that the implications of this phenomenon could be enormous, but one stubborn obstacle has stood in their way: reaching and maintaining the temperatures necessary for superconductivity in these metals is difficult and in most instances prohibitively expensive.

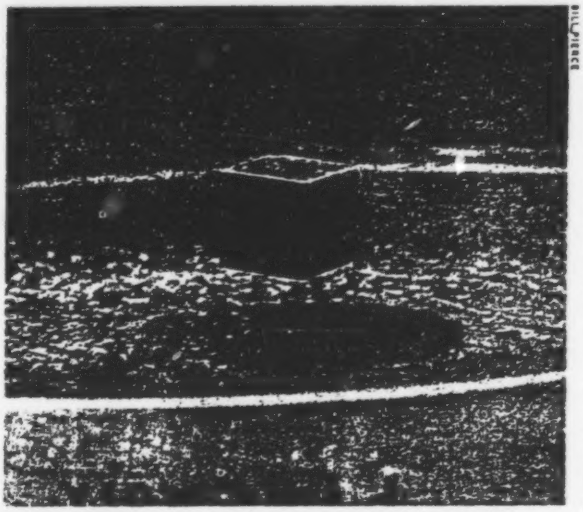
Now, in a series of rapid-fire discoveries, researchers around the world have begun concocting a different class of materials that become superconductors at significantly higher temperatures—levels



that, while still beyond the reach of a kitchen refrigerator, are easier and less costly to attain. These achievements have had an electrifying effect on a subject that just a year ago would have elicited yawns from physicists and blank stares from politicians. Indeed, hardly a week has passed since the New York City meeting without reports from competing scientists—in the popular press as well as in professional journals—of new superconducting materials and ever higher temperature ranges. An effect that once could be detected only with sophisticated equipment has become a common sideshow at conferences: a sample of one of the new materials is placed in a dish of liquid nitrogen, and a magnet placed above it. Since superconductors repel magnetic fields, a phenomenon called the Meissner effect, the magnet remains suspended in midair.

Fun and games aside, though, the competition is growing more intense. Researchers around the world are canceling vacations, ignoring their families, moving cots into their labs and subsisting on takeout food and microwave popcorn. "We've been working since right after Christmas," says Physicist J.T. Chen of Wayne State University in Detroit. "We do experiments almost every day. Sometimes we sleep only three or four hours. Maybe it was like this when the transistor was invented, but in my personal experience this is unique." Says Japanese Chemist Kohji Kishio: "The race is for the Nobel Prize."

The world's leading industrial nations are in a race of another kind. Quick to recognize the commercial potential of the new development, Japan's Ministry of International Trade and Industry plans to subsidize private-sector research, and will establish a center in Nagoya to test equipment made from superconducting materials. In Washington, the Department of Energy has decided to double this year's research support for superconductors to $40 million; it is also compiling a computerized database that will enable American scientists to keep up to date on fast-breaking superconductor research results, and will co-sponsor a White House conference on superconductivity this summer. "It's a monumental subject," says Energy Secretary John Herrington. "It ranks up there with the laser." In the Senate, Minnesota Republican David Durenberger has co-sponsored a bill calling on the President to form a national commission to coordinate superconductivity research and development. Says Durenberger: "We cannot stand idly by while Japan targets another industry for industrial [illegible]." Last week the National Science [illegible] announced $1.6 million in grants to help keep the U.S. competitive in superconductivity research.


BILL PIERCE

A magnet levitates over a disk of superconductive material

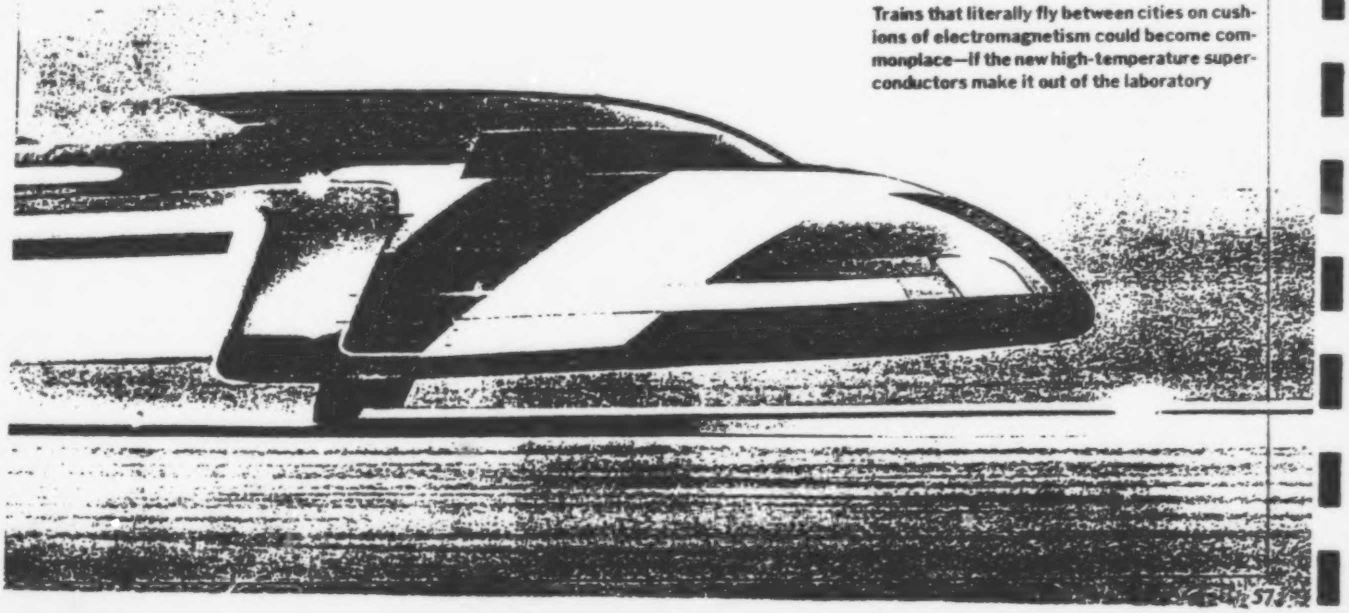
The superlatives roll in. "In terms of the societal impact, this could well be the breakthrough of the 1980s in the sense that the transistor was the breakthrough of the 1950s," says Alan Schriesheim, director of Argonne National Laboratory near Chicago. Indeed, scientists hardly know where to start in describing the bonanza that superconductors could yield.

Take the transmission of electricity, for example. As much as 20% of the energy sent through high-tension lines is now lost in the form of heat generated as the current encounters resistance in the copper wire. If the electricity could be sent through superconducting cable, however, not a kilowatt-second of energy would be lost, thus saving the utilities, and presumably consumers, billions of dollars. Furthermore, at least in theory, all of a large city's electrical energy needs could be supplied through a handful of underground cables.

Elimination of heat caused by electrical resistance could have a profound effect on the design and performance of computers. In their efforts to produce smaller and faster computers, designers try to cram more and more circuits into chips and ever more chips into a tiny space. But they are limited in their scaling-down endeavors by heat: even the tiny currents in computer circuits generate enough cumulative heat to damage components if they are too tightly packed. Today's personal computers could not operate without vents or inter-

ILLUSTRATION FOR TIME BY PHILIP CASTLE

Trains that literally fly between cities on cushions of electromagnetism could become commonplace—if the new high-temperature superconductors make it out of the laboratory



nal fans to dissipate the heat. Now, with practical superconducting circuitry on the horizon, computer designers may soon see the way clear for even more remarkable miniaturization.

In still other applications, the intense magnetic fields that might someday be generated by the new superconductors should benefit any device that now uses electromagnetism in its operation—medical diagnostic imaging machines, magnetically levitated trains, fusion-energy generators—and will undoubtedly spawn a host of new machines. Electric motors could increase in power and shrink in size.

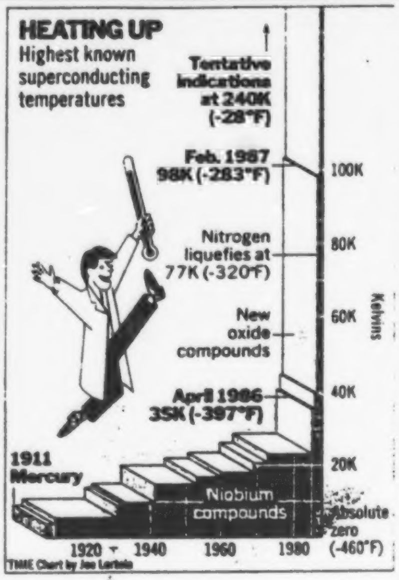
But these are just the most obvious examples. Scientists like Robert Schrieffer, who shared the 1972 Nobel Prize in Physics for the first successful theory of how superconductivity works, believe its most dramatic applications have yet to be conceived. "When transistors were first invented, we knew they'd replace tubes," Schrieffer says. "But no one had any idea there would someday be large-scale integrated circuits." Robert Cava of Bell Labs agrees. "We don't know where this will lead," he says. "It's exciting—and I guess frightening at the same time."

From the time that Dutch Physicist Heike Kamerlingh Onnes discovered superconductivity in 1911 until the recent rash of breakthroughs, there was only one way to produce the phenomenon: by bathing the appropriate metals—and later, certain metallic alloys—in liquid helium. This exotic substance is produced by lowering the temperature of rare and costly helium gas to 4.2 K (−452° F), at which point it liquefies. But the process is expensive and requires considerable energy. Furthermore, unless the liquid helium is tightly sealed in a heavily insulated container, it quickly warms and vaporizes away. Thus the practical use of superconductors has been limited to a few devices—an experimental Japanese magnetically levitated train, a few giant particle accelerators and medicine's magnetic-resonance imaging machines—that operate with intense magnetic fields.

But in the past year and a half physicists have stumbled on an unusual class of ceramic compounds that change everything. They too must be cooled to become superconductors, but only to a temperature of 98 K (−283° F). And that suddenly brings superconductivity into the range of the practical; liquid helium can be replaced as a coolant by liquid nitrogen, which makes the transition from a gas at the easily produced temperature of 77 K (−320° F). Moreover, liquid nitrogen is cheaper by the quart than milk and so long-lasting that scientists carry it around in ordinary thermos bottles. Also, the ceramics may be able to generate even more intense magnetic fields than metallic superconductors. Thus, if these new substances can be turned into practical devices—and most scientists believe they can—technology will be transformed. Declares Arno Penzias, vice president for research at Bell Labs: "The recent advances in the field of superconductivity are almost without comparison."

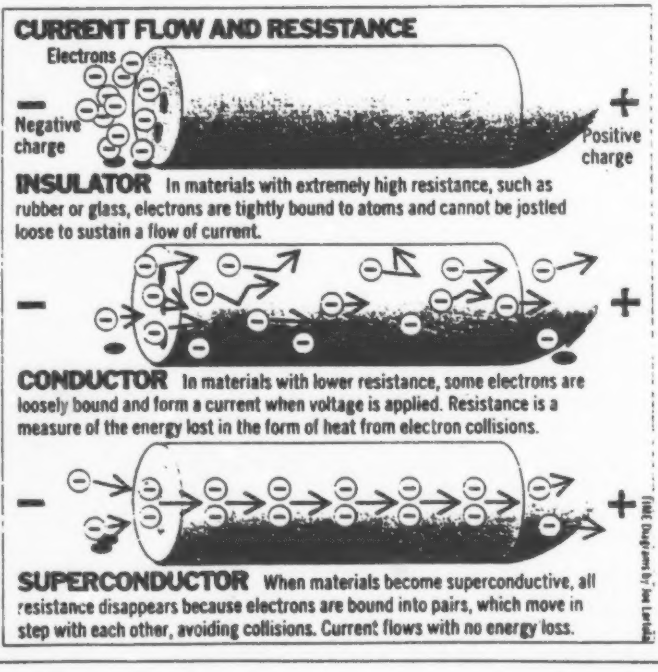
HEATING UP

Highest known superconducting temperatures



TIME Chart by Joe Lertola

CURRENT FLOW AND RESISTANCE



INSULATOR In materials with extremely high resistance, such as rubber or glass, electrons are tightly bound to atoms and cannot be jostled loose to sustain a flow of current.

CONDUCTOR In materials with lower resistance, some electrons are loosely bound and form a current when voltage is applied. Resistance is a measure of the energy lost in the form of heat from electron collisions.

SUPERCONDUCTOR When materials become superconductive, all resistance disappears because electrons are bound into pairs, which move in step with each other, avoiding collisions. Current flows with no energy loss.

TIME Diagrams by Joe Lertola

Success and celebrity have been a long time in coming to the field of superconductivity. "Until recently," says John Ketterson, a physicist at Northwestern University, "people were glum. There hadn't been a breakthrough in a long time. Funding was drying up. This has sent everyone back into the field with a new burst of enthusiasm." Although Kamerlingh Onnes envisioned early on that his discovery might pave the way for extremely powerful, compact electromagnets, he and other experimenters were stymied by a strange phenomenon: as soon as enough current was flowing through the then known superconductors (lead, tin and mercury, among others) to generate significant magnetic fields, the metals lost their superconductivity.

It was not until the 1950s that scientists discovered alloys, such as niobium tin and niobium titanium, that keep their superconductivity in the presence of intensely strong magnetic fields. And it was not until the '60s and '70s that the manufacture of large superconducting magnets became standardized. But progress toward the other goal of superconductivity researchers, pushing the phenomenon into a practical temperature range, was even slower. By 1973, some 62 years after Kamerlingh Onnes had found superconductivity in mercury at 4.2 K, scientists had upped the temperature to only 23 K, using an alloy of niobium and germanium. After 1973: no improvement.

That was the situation in 1983 when Karl Alex Müller, a physicist at the IBM Zurich Research Laboratory in Switzerland, decided to pursue an approach to superconductivity that had met with limited success in the past. Instead of using the kind of metallic alloys that held the existing record, he turned his attention to the metallic oxides (compounds of metals and oxygen) known as ceramics. Some theorists had suggested ceramics as potential superconductors even though they were poor conductors at room temperatures. In fact, ceramics are often used as insulators—for example, on high-voltage electric-transmission lines.

Müller and his colleague, Johannes Georg Bednorz, tinkered with hundreds of different oxide compounds over the next few years, varying quantities and ingredients like alchemists in search of the philosopher's stone. Finally, in December 1985, they came across a compound of barium, lanthanum, copper and oxygen that seemed promising. When Bednorz tested the compound, he was startled to see signs of superconductivity at an unprecedented 35 K, by far the highest temperature at which anyone had observed the phenomenon. Could this result be correct? Aware of some hastily made superconductivity claims that later could not be reproduced, the IBM team proceeded cautiously, painstakingly repeating their experiments. In April 1986, Müller and Bednorz finally submitted the findings to the German journal *Zeitschrift für Phy-*

sik, which published it five months later.

As Müller had anticipated, other physicists were skeptical. For one thing, the IBM scientists had lacked the sensitive equipment to test for the Meissner effect, the surest proof of superconductivity, and thus could not confirm it in their report. More important, in a field where improvements of a few degrees were reason for celebration, this great a temperature leap seemed unlikely. Douglas Finnemore, a physicist at Iowa State University, admits that he was among the doubters. "Our group read the paper," he says. "We held a meeting and decided there was nothing to it."

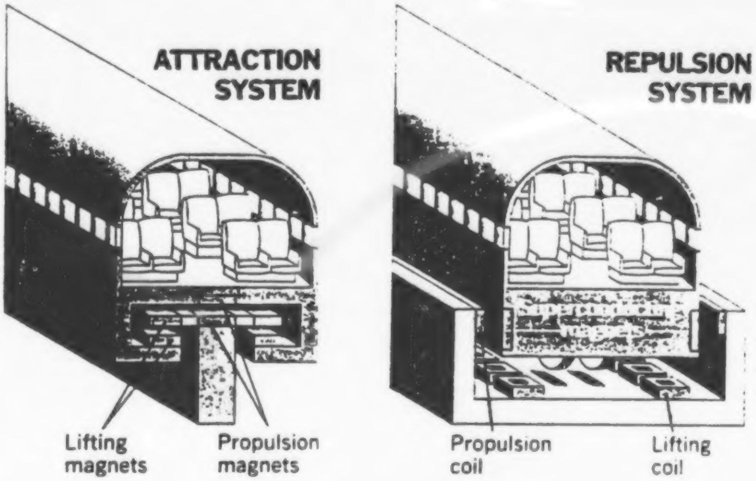
Not everyone was so quick to dismiss the discovery. Scientists from the University of Tokyo took a look at the substance. Says Müller: "The Japanese weren't smiling, and they confirmed it. Then the United States sat up." By the end of the year, confirmation had come from China and the U.S., and suddenly a nearly moribund branch of physics was the hottest thing around. Large industrial and government laboratories jumped in; so did major universities. At Bell Labs, a team led by Bertram Batlogg and Ceramist Cava had launched their own program of alchemical tinkering. Soon they had manufactured a similar compound that became a superconductor at 38 K, one-upping their archrivals at IBM. "That's when the hysteria started," says Cava. "The place was abuzz with excitement."

But Bell Labs too was soon to be upstaged. For among those who had given early credence to the news from Zurich was a small, modestly equipped team of researchers headed by Paul C.W. Chu of the University of Houston. Chu had been studying superconductivity since 1965; now he and his group, including scientists from the University of Alabama, quickly reproduced the IBM results and moved on to their own experiments.

Since the Houston lab had special equipment for testing materials at high pressure, Chu wondered what would happen if he pressurized the IBM compound. "Using known theories," he says, "you don't expect the transition temperature to go up rapidly under pressure, but it shot up like a rocket. It suggested to us that there might be some new mechanism involved." That unexpected result, says Chu, played right into what he considers his group's strong suit: "We feel we have an advantage over some other groups because we are not confined to conventional thinking. We think wildly." Chu found that the compound remained a superconductor up to 52 K (−366° F) when subjected to from 10,000 to 12,000 times normal atmospheric pressure.

Forcing the pressure higher than that had no effect; it was time for more wild thinking. Chu reasoned that the high pressure worked because it squashed the compound's molecular structure and that this somehow boosted its superconducting temperature. Since more pressure did no

Trains That Can Levitate



One item is on everyone's list of potential benefits of high-temperature superconductors: maglevs, or magnetically levitated superfast trains. It is a safe prediction, since the new materials give promise of electromagnets far more powerful and economical than those in use today. And it is the electromagnet that lifts and propels existing maglevs in Japan, West Germany and Britain.

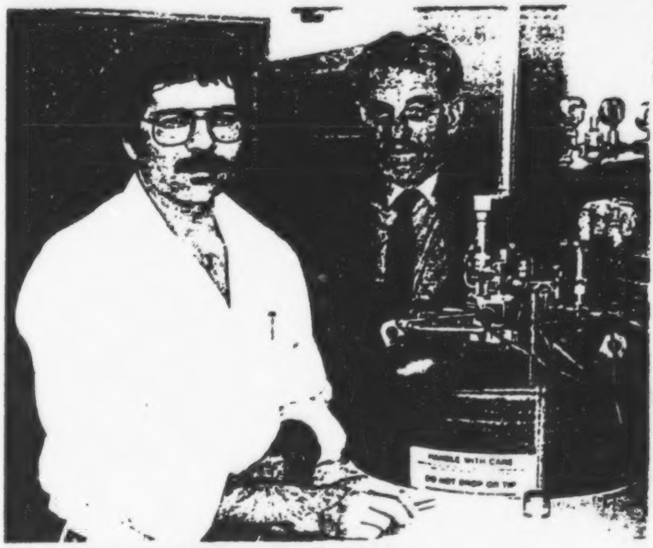
As long ago as 1979 an unmanned Japan Railways Group prototype fitted with low-temperature superconducting electromagnets hit 321 m.p.h. on a test track; a version carrying three passengers made it to 249 m.p.h. earlier this year. That beats any conventional rival, including Japan's celebrated bullet train, which goes as fast as 149 m.p.h., and the French TGV, which provides the world's fastest regularly scheduled rail service, at speeds of up to 186 m.p.h.

Japan's maglev is faster because instead of pounding along a set of rails, it floats four inches above a guideway on a cushion of magnetic force: there is no friction to slow it down, no fear of derailment on a section of bent track. This maglev has wheels, but the only times it uses them are while picking up speed before lift-off and while slowing down after landing.

The principle behind the maglev is simple: opposite magnetic poles attract each other; like poles repel. In Japan's version, eight superconducting electromagnets are built into the sides of each train car, and thousands of metal coils are set into the floor of the guideway. When the train is in motion, the electromagnets on the train induce electric currents in the guideway coils, which then themselves become electromagnets. As power is increased, the opposing sets of magnets repel each other and lift the train into the air. Two other rows of electromagnets, one on each wall of the U-shaped guideway, repeatedly reverse polarity to push or pull on the coach's magnets and thus move the train forward.

In planning the train, Japanese engineers chose superconducting magnets because for a given input of electricity they generate more intense magnetic fields—and thus greater lifting and propulsion power—than conventional electromagnets. The drawback: the liquid-helium coolant needed for the superconducting magnets is expensive, and a heavy compressor is required in each coach to reliquefy the evaporating helium. That is why maglev engineers are excited by the idea of the new high-temperature superconductors, which would use considerably less expensive liquid nitrogen as a coolant and require far smaller compressors. The developments of the past few months, says Research Chief Kazuo Sawada, who has been in on the project from the beginning, are a "promising sign."

In West Germany, on the other hand, the new superconductors are of little interest to maglev engineers, who abandoned superconducting magnets in 1979. They opted to use conventional electromagnets instead. The German system is based on magnetic attraction, not repulsion. The magnets are on assemblies attached to the cars' undercarriages that curve around and under the crossbar of a T-shaped track. When the magnets are energized, they pull themselves up toward the crossbar's metallic underside and the car is lifted into the air; magnets in the track provide propulsion. Which technique is better? Both have advantages. The German maglev is simpler and less expensive to operate. But so far the Japanese trains are about 100 m.p.h. faster.



Pioneers Bednorz and Müller in their Zurich lab

They got a skeptical reaction from other physicists.

good. Chu decided to compress the molecules in a different way—from within. He replaced the barium with strontium, which is similar chemically but has a smaller atomic structure. Sure enough, the temperature rose again, to 54 K, then stopped. So he turned to calcium, an element with even smaller atoms. This time the temperature dropped. It appeared to be a dead end.

Now Chu's team tried lanthanum, the rare-earth* component of the IBM compound. Maw-Kuen Wu, head of the team's Alabama unit and a former graduate student of Chu's, replaced the lanthanum with another rare-earth element, yttrium.

The new substance showed so much promise that Chu filed a patent application on Jan. 12. That promise was soon fulfilled. At the end of the month, after subjecting their creation to a series of heat and chemical treatments, Wu and his assistants began chilling a bit of the compound, by dousing it with liquid nitrogen, and sending an electric current through it. To their amazement, the sample's resistance began to drop sharply at a towering 93 K. Recalls Wu: "We were so excited and so nervous that our hands were shaking. At first we were suspicious that it was an error." But a few days later he and Chu duplicated the feat in Houston and even bettered it by 5°.

ARTHUR SHAY

John Bardeen explaining his theory

The accomplishment of Chu and his team did nothing to dampen their competitors' enthusiasm. Indeed, the effect was just the reverse. In order to protect his patent, Chu refused to disclose the exact composition of his new material before the formal report was published in the March 2 *Physical Review Letters*, but other scientists thought they could easily guess its makeup and went to work.

At the University of Illinois, Physicist Donald Ginsberg raced out to buy an air mattress and an alarm clock, anticipating a spate of all-nighters. At IBM's Almaden Research Center in San Jose, scientists successfully duplicated the compound, analyzed its crystal structure and passed the information on to the company's labs in Yorktown Heights, N.Y., where their colleagues were able to make thin films of the substance literally overnight. At the University of California, Berkeley, a group that included Theoretical Physicist Marvin Cohen, who had been among those predicting superconductivity in the oxides two decades ago, reproduced the 98 K record, then started trying to beat it. "I'm a standard American scientist," says Cohen. "My definition of research is to discover the secrets of nature—before anyone else."

In short, says Douglas Scalapino, of the University of California at Santa Barbara, recent developments are something like the breaking of the four-minute mile. Beforehand, it had been considered nearly impossible; afterward, "you could go to any track meet and some guy was breaking it." The activity, says Cava, "is more exciting than a supernova. Astrophysicists can watch it, but when it happens, it happens and it's gone. In superconductivity, the events are still going on, and the physics is just beginning to pour in."

So are the scientific papers. Says Metallurgist Frank Fradin, director of Argonne's materials science division, who is also an associate editor of *Physical Review Letters*: "As of [illegible] 98 papers submitted on the subject, and only a small fraction of them will ever get published. Progress is so rapid that a result of two to three weeks ago is already out of date. We've had to institute a whole new system to speed up the publication process." One important discovery: at least a dozen different compounds, all subtly different from the one Chu found, appear to act as high-temperature superconductors.

While scientists know the chemical composition of the new class of superconductors, they are less certain about how they work. True, a theory exists that explains low-temperature superconductivity. It is known as BCS, from the initials of Author John Bardeen and his colleagues Leon Cooper and Robert Schrieffer, who shared the 1972 Nobel Prize for Physics for their effort. But BCS may not apply to the strange goings-on at higher temperatures.

Ordinary conductivity, the measure of a material's ability to transmit electrical current, is determined by events that take place at the atomic level. Atoms consist of a tiny dense nucleus that contains positively charged protons and chargeless neutrons. Around the nucleus whirl the negatively charged electrons, residing in shells with shapes determined by the electrons' energy levels.

In many atoms, particularly those of metallic conductors, the outer shell has a number of empty slots, and the electrons that it does contain are not bound as tight-

CONOLLY—PICTURE GROUP

Paul Chu with a flask of liquid nitrogen

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*The so-called rare earths, a group of 17 chemical elements, are not rare at all: yttrium, for example, is thought to be more abundant than lead. These elements were mislabeled because they were first found in truly rare minerals.

y to it as those in the inner shells. Just as the sun's gravitational pull is weaker on distant Pluto than on nearby Mercury, the hold of an atomic nucleus is also weaker on electrons in the outermost layers.

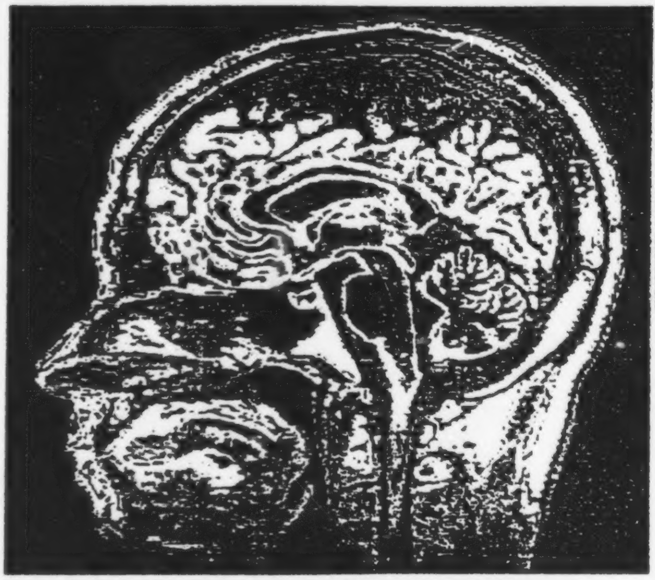
So when an electric current—which is simply a stream of moving electrons—flows in a conductor, electrons move from empty slot to empty slot in the outer shells of the atoms. A material like rubber, on the other hand, is an insulator: it consists largely of atoms with completely filled, stable outer shells. Thus when voltage is applied, electrons have no empty slots to move into, and no current flows.

But even the best of ordinary conductors have some resistance to the flow of electrical current. The reason: as current passes through, some of the electrons collide with other electrons, thus dissipating their energy in the form of heat. According to the BCS theory, these collisions are avoided in superconductivity. "What causes a material to become superconducting is a phase change,"* explains Bardeen, now a professor emeritus at the University of Illinois. "You can think of it as electrons condensing into a new state." That state involves the pairing of electrons and a kind of group discipline.

Iowa's Finnemore compares the movement of the electrons in a superconductor to a crowd moving across a football field. "If they act as individual particles," he explains, "they will bump into each other and scatter. That's the equivalent of electrical resistance. But suppose someone starts counting cadence, and everyone locks arms and marches in step. Then even if one person falls into a chuckhole, he won't fall because his neighbors hold him up." Thus in a superconductor electrons move unhindered.

While the BCS theory works well near absolute zero, some physicists think it will have to be modified or even scrapped as an explanation for the behavior of higher-temperature superconductors. According to Bardeen, his theory can explain superconductivity up to around 40 K. But at 90 K, he says, "I think it's highly unlikely. We no doubt are going to need a new mechanism." In fact, says Schrieffer, "superconductivity may turn out to have as many causes as the common cold."

Confusion at the level of theory has put no damper on the orgy of speculation about potential applications. Some ideas involve upgrading existing superconducting technology; others push marginal technology into the realm of the profitable; still others raise the prospect of entirely new uses of the phenomenon.



CNRI/SCIENCE PHOTO LIBRARY—PHOTO RESEARCHERS

Magnetic-resonance cross section of soft tissues in an adult's head

Smaller, less expensive, more powerful medical imaging machines.

Giant particle accelerators are one target for possible upgrading. Currently the most powerful such devices use conventional superconducting electromagnets. If high-temperature superconducting magnets can be developed, millions of dollars could annually be saved in electrical and liquid-helium bills.

Electromagnets are also crucial to fusion energy, which depends on fusing atoms (the same process that powers the sun), rather than splitting them. Key to one promising fusion process, which is under development in several countries, is a "bottle" composed not of any material substance but of powerful magnetic fields, generated at great expense by conventional electromagnets. Such fields are the only envelopes that can contain and squeeze atoms together at the hundred-million-degree temperature required to initiate fusion. But superconducting magnets, especially warm-temperature ones, could produce more intense fields at less expense and thus could "help make fusion power possible and practical," says Harold Furth, director of Princeton University's Plasma Physics Laboratory.

In medicine, superconducting magnets are at the heart of magnetic resonance-imaging machines. The magnets' powerful fields first align the atoms of the body. Then a pulse of radio waves knocks them momentarily out of alignment. When the atoms return to their previous attitudes, they emit radiation that produces detailed images of the body's soft tissues. MRI machines in use today are enormous (6 ft. by 8 ft. by 10 ft.), largely because of the more than $100,000 worth of bulky insulation required to preserve the liquid helium coolant, which costs an additional $30,000 annually. The improved economics of the new superconductors, says Walter Robb, of General Electric's Research and Development Center, should eventually enable medical institutions to install many more MRI machines, which are invaluable for diagnosing disorders like brain tumors.

High-temperature superconducting magnets may become important in the maglev, or magnetically levitated, trains under development in Japan and West Germany. And scientists at Japan's Mercantile Marine University in Kobe have already developed a working scale model of a ship with a propulsion system based on magnetism. Physicist Yoshiro Saji sends current through the seawater from an on-board electric generator via ship-bottom electrodes. A superconducting magnet, also on board, creates a strong magnetic field. As the electromagnetic field produced by the electric current pushes against the field of the magnet, the ship moves forward. Saji has already moved up his timetable and hopes to complete a 100-ton "magship" within four years. "Thanks to the new materials," he says, "magnets will be lighter and easier to handle. Once we can replace liquid helium with liquid nitrogen, the whole process of outfitting the ship will be simplified. It's a fantastic development."

On a smaller scale, superconductors have already been used to create superfast electronic switches called Josephson junctions (after Nobel Laureate Brian Josephson, the British physicist who discovered the principle on which they are based), which until now could operate only at liquid-helium temperatures. For both technical and economic reasons, IBM abandoned its Josephson junction project in 1983. But IBM Physicist Sadeg Faris quit the company, obtained licenses for the technology and formed Hypres, Inc., which has begun marketing its first Josephson junction product—a high-speed oscilloscope. Says Faris: "The new materials are at a primitive stage, but we're anxious to exploit them to bring down costs and improve speed." Since switches are a limiting factor in computer speed, an economical Josephson junction could prove invaluable.

At Westinghouse, scientists are working on the idea of using superconductors for electric-power production. Today's nonsuperconducting generators produce electricity by spinning wire-wrapped rotors in a magnetic field; their output is typically some 300 megawatts a generator. If the field were generated even by conventional superconducting electromagnets, says Research Director John Hulm, the output could be doubled. The benefits would be even greater with high-temperature superconductors.

And then there are the daydreams: giant underground loops of superconduct-

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*The most familiar example of a phase change is the transformation, at 32° F, of water from a fluid into crystalline ice.

SSC: Lord of the Rings

When President Reagan formally endorsed the superconducting supercollider (SSC) last January, it seemed likely that the $4.4 billion, 53-mile-circumference particle accelerator would be completed on schedule in 1996. But the recent breakthroughs in superconductivity have raised some questions about the 10,000 powerful magnets needed to keep streams of protons on course as they speed around the huge ring.

Should SSC designers move ahead with plans to use conventional, low-temperature superconducting magnets, known quantities that are already in place and operating at Fermilab's Tevatron accelerator in Batavia, Ill.? Or should they hold off indefinitely, awaiting development of the new high-temperature superconducting variety, which may someday be able to generate even stronger magnetic fields at less cost?

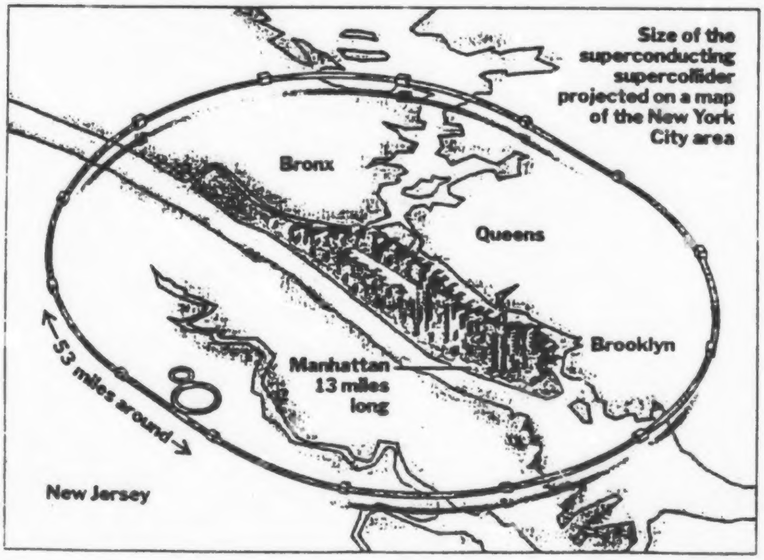
Some scientists, particularly those opposed to the SSC for other reasons, have expressed concern that the rapid developments in superconductivity could warrant a redesign of the accelerator. "It might be possible to shrink the radius down to ten miles," says Cornell Physicist James Krumhansl, president-elect of the American Physical Society. "What I say is, let's put the matter into one more year of research and development and review it next year."

Still, it is not at all certain that the new ceramic superconductors will ever be capable of carrying the high electric currents necessary for generating strong magnetic fields. And no one has yet fashioned the inherently brittle material into a wire flexible enough to be wound into effective coils, though many research groups have reported progress. Says Burton Richter, director of the Stanford Linear Accelerator Center: "It took 25 years to turn the present superconductors from a laboratory curiosity into something that could be made into miles of cable. These are even more difficult materials to work with."

Leon Lederman, director of Fermilab, agrees. "Even if, miracle of miracles, in the next two years they solve all the problems of brittleness and high current," he says, "we would still need lots of experience to understand the materials well enough to make good magnets A superconducting accelerator magnet is a Swiss watch of precision." One problem: superconducting magnetic fields are so strong they can actually deform the accelerator magnets that produce them. While physicists have learned to deal with that phenome[illegible] Fermilab, they have no idea how to handle fields that could be many times as strong.

Proponents of delay, Lederman charges, are more concerned about the tremendous cost of the SSC, which they think will siphon federal funds away from other branches of science: "They see the new superconductors as a weapon with which to slay the SSC."

Krumhansl excludes himself from that category. "It would be wrong to say I'm against the SSC," he says. "It's great scientifically. In fact, it's mind blowing. The problem is that over the past five years there has been a slow starvation of what I call 'small science.' I say first get small science in good shape, and then by all means proceed with the SSC."


Size of the superconducting supercollider projected on a map of the New York City area
Bronx
Queens
Brooklyn
Manhattan 13 miles long
← 53 miles around →
New Jersey

ing cable that can store vast amounts of electricity for later use; cars that run on tiny, powerful electric motors, drawing current from superconducting storage devices. But even the daydreams are taken at least somewhat seriously. At Ford, for example, a study group has been assembled to rethink the feasibility of the electric car in light of the recent advances in superconductivity. Says IBM Physicist John Baglin: "The question is not 'How can we take this material and do something everyone has wanted to do?' but 'How can we do something that no one has yet imagined?' " Some tongue-in-cheek suggestions overheard at a superconductor meeting: superconducting ballroom floors and rinks that would enable dancers and skaters literally to float through their motions.

All the applications, though, depend on bringing the technology out of the lab, and despite the bubbly confidence of many scientists, obstacles remain. One is the need to form the new materials into usable shapes. While metals bend, anyone who has dropped a dinner plate knows that ceramics do not. And a flexible material has a big advantage over a brittle one if it is to be coiled around an electromagnet. Says Osamu Horigami, chief researcher at Toshiba's Energy Science and Technology Laboratory: "To get a magnet or coil or even a wire we could use with complete confidence could take another five years." Agrees Hulm: "It will take extraordinary engineering to solve the brittleness problem."

IBM scientists may already have a partial answer: they announced last week that the new compounds can be "spray-painted" onto complex forms, where they solidify. Says IBM Scientist Jerome Cuomo, who described the technique at the American Ceramic Society conference in Pittsburgh: "This opens the door wider than ever to the fabrication of useful objects made of superconducting materials."

More fundamental is the fact that while the new ceramics remain superconductors at high temperatures and can withstand intense magnetic fields, they can as yet carry only about a hundredth of the current capacity of conventional superconductors. And because the amount of current flowing through the magnetic field determines its strength, scientists are concerned that a quick fix may not be in sight. Warns GE's Robb: "What we need now is a second invention that would modify copper oxides to allow high currents to flow at high temperatures. There's a fifty-fifty chance that second invention will ever be made."

Finally, there is a human problem that could hinder progress in the suddenly vigorous field of superconductivity: the increasing unwillingness of scientists to exchange information about their experiments. At the Woodstock of physics meeting, for example, some were miffed when Stanford researchers, following their presentation, refused to divulge further details of their research; they had been advised by patent attorneys to reveal as little as possible until their work was legally protected. The competition extends beyond legal rights. Two weeks after Chu's record-breaking temperature was announced, the Berkeley team independently came up with the same superconducting compound. They immediately mailed a report of their results to *Physics Letters*, hoping it would be received before Chu's paper was published. Reason: they wanted to establish that they had not merely copied his work.

Still, there are hints that some of the physical barriers, at least, are starting to fall. At the March meeting, scientists were already showing rings and flexible tapes made of high-temperature superconductors; by the end of the month, teams at IBM, Bell Labs, Toshiba, Argonne and a handful of other places were developing wire-thin ceramic rods. Says Toshiba's Horigami: "We weren't even sure this was possible. When we finally had a wire that could potentially be coiled, there was absolutely no way to measure our sense of triumph." Argonne Ceramist Roger Poeppel now talks of building a furnace ten feet long to fire his group's wire almost continuously as it is extruded. "We think it will be flexible enough to twist into cable," he says, "and cable is the building block for magnetic coils and electrical transmission lines. With two miles of wire, we'll make a superconducting magnet. To get a practical device is now the race."

Later, in April, scientists at Stanford and IBM announced that they had made thin films of the new substances, important for computer applications. The spotlight then shifted to IBM Researchers Robert Laibowitz and Roger Koch, who reported that they had made their own thin film into a working gadget called a SQUID (for superconducting quantum interference device). Such tools are already used in low-temperature versions to measure extremely faint magnetic fields. They are also employed by physicists in the search for elusive gravity waves and magnetic monopoles, predicted by some theories but not yet observed. Medical researchers use SQUIDs to detect the minute fields generated by electrical activity within the brain. High-temperature SQUIDs should make all these searches a little easier.

Other scientists are seeking a better understanding of why the ceramics become superconductors. Many labs have taken pictures of the materials with electron microscopes, pulsed beams of neutrons, X rays and ultrasound. A team of Bell Labs and Arizona State scientists has produced electron-microscope photographs that show defects in the compound's crystalline structure. Says Team Leader Abbas Ourmazd: "We don't quite understand what role the defects play, but it raises some provocative questions. Is it the perfect material that is superconducting? Or is it the defects? If it turns out that it is the defects, then we will want to control them and increase their density and put them in intentionally."

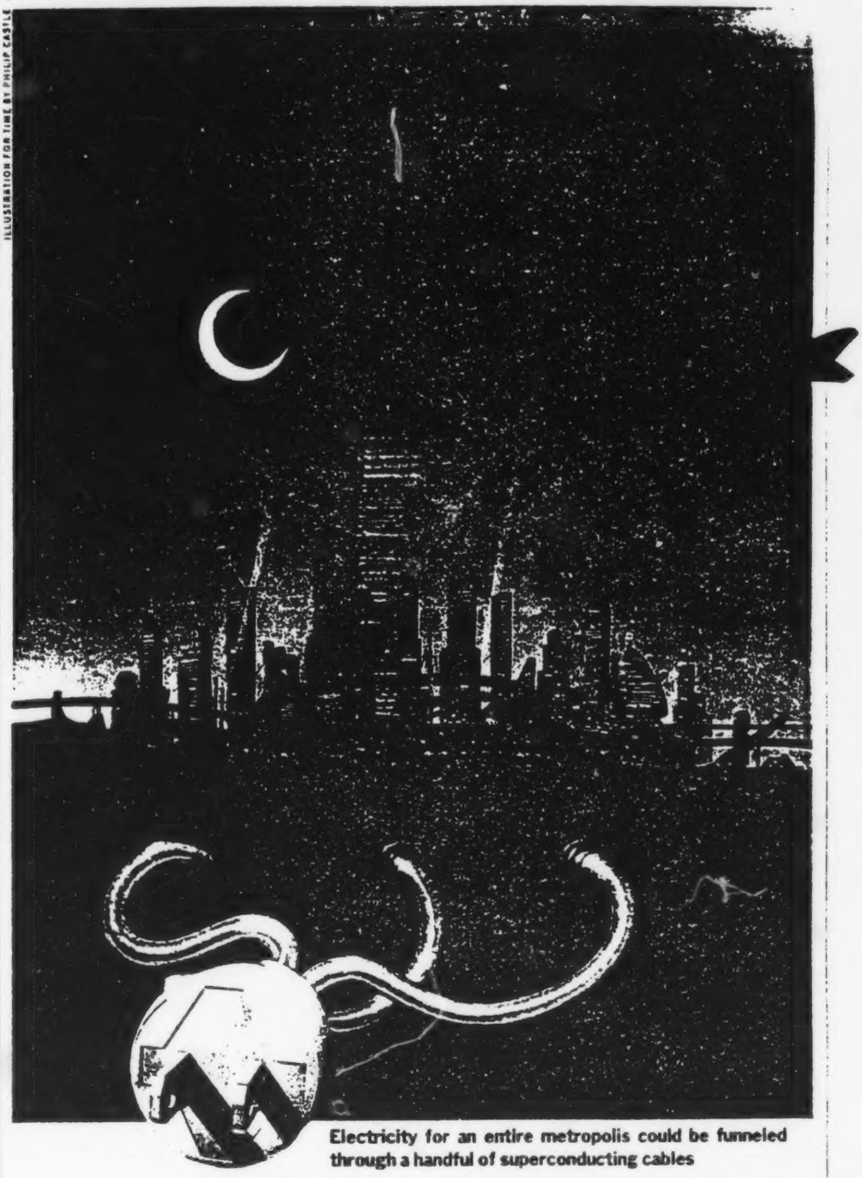


ILLUSTRATION FOR TIME BY PHILIP CASTLE

Electricity for an entire metropolis could be funneled through a handful of superconducting cables

Most intriguing of all are reports that the temperature record set by Chu and since matched by dozens of other researchers has already been surpassed. Some physicists have even reported superconductivity-related effects—though not true superconductivity—at the torrid heights of 240 K, or −27° F, which is warmer than many wintry nights in North Dakota.

Those results suggest an intriguing possibility. Says Bell Labs' Penzias: "Transition temperatures have increased by a factor of four in the past year. If temperatures are raised by another factor of four in the same period of time, we'll have room-temperature superconductors in less than a year." Adds IBM's Praveen Chaudhari: "All the mental barriers are gone. No one is asking how high it will go anymore." If room-temperature superconductivity is achieved, whether in a year or in a score of years, its impact will be incalculable. The need for refrigerators and insulation, even for liquid nitrogen, will be gone. And the costs of this still futuristic technology could drop more dramatically than anyone expects. Says IBM's Paul Grant: "We're looking. Everyone is." Adds IBM's William Gallagher: "We shouldn't let our imaginations be constrained by things we now know about. We're just not able to imagine the things you can do." ***—By Michael D. Lemonick. Reported by Thomas McCarroll/New York, J. Madeleine Nash/Chicago and Dennis Wyss/San Francisco***

APPENDIX C

PROPOSAL TO B.C. SCIENCE COUNCIL FOR A BRITISH COLUMBIA REMOTE LIBRARY ON HIGH-TEMPERATURE SUPERCONDUCTORS

Proposal to B.C. Science Council for a

BRITISH COLUMBIA REMOTE LIBRARY ON HIGH–TEMPERATURE SUPERCONDUCTORS

Jess Brewer

Dept. of Physics, Univ. of B.C.

Terms of Reference

The Science Council of British Columbia has charged a subcommittee on high-T_c superconductors (HTSC) to describe local research activity in this field and to suggest ways in which Council can facilitate local scientific progress and speed the transfer of relevant technological advances to the industrial sector.

As a member of that subcommittee I have agreed to outline a scheme whereby Council can make an important and substantive contribution without compromising its normal role of facilitating applied research and development. It is my opinion that the key to competitiveness in HTSC research, for both fundamental and applied science, is *superior information handling*, which can be aided immensely by an independently funded *remote library* facility in B.C.

The HTSC Information Explosion

Today's scientific community is increasingly at risk of inundating itself in a deluge of literature far beyond any individual scientist's ability to digest. The overspecialization driven by this phenomenon is a familiar nightmare to us all.

Never has this been so vividly illustrated as in the "superconductivity revolution of 1987" which, in one year, has enlisted tens of thousands of "troops" and generated a similar number of scientific papers. There are probably dozens of brand-new *journals* devoted to various aspects of HTSC that did not exist a year ago. It seems painfully obvious that a serious researcher in this field is caught between the necessity of keeping up with the literature (to avoid duplication of already completed work and to prevent the spectacle of aimless ignorance) and the pursuit of his or her own research.

Moreover, an industrial scientist looking for possible applications of HTSC must sort through the same mountain of literature to find a paper describing the necessary process or establishing patent rights.

Computerized Literature Searches

Fortunately, there are several types of computerized literature searches already publicly available that will scan the titles of vast numbers of papers for designated keywords, etc., and deliver a list of relevant papers on the desired subject.

One such "HTSC Database" is the *SUPCON* database at TRIUMF, which can sort through papers looking for any combination of keywords, authors or journal entries. So far *SUPCON* has been provided *free* as a public service; unfortunately, it is almost useless at this stage because it contains only a tiny fraction of the HTSC literature; this is simply because *sorting and entering* the incoming lists of known papers is a full time job for at least one or two people, and the scientists who have implemented *SUPCON* and maintained it so far cannot be expected to put aside their own research to become librarians. The main reason for mentioning *SUPCON* at all is that the papers listed are also stored in filing cabinets at TRIUMF and are mostly *preprints* (manuscripts circulated prior to submission for publication) rather than copyrighted *reprints* (copies of published works).

Computer searches of gigantic scientific literature databases are commercially available as well. A noteworthy example is the CAN/OLE search of the gigantic INSPEC database; this is supported by the Canadian Institute for Scientific and Technological Information (CISTI) and is available at most large libraries. I tried it out on papers containing both "muon" and "superconduct" in the title or keywords, and obtained a list of around 40 papers including some I had not been aware of; the procedure took about half an hour and cost around $75. I was then able to look up several of the papers I wanted in the UBC Library and ordered the rarer ones from CISTI using an Interlibrary Loan request; delivery time for the copied papers was estimated to be 1–2 weeks, at a cost of (I think) roughly $10/paper.

I noticed that INSPEC is about 3 months out of date - that is, the most recent papers listed are about 3 months old. This is actually fairly impressive for such a huge database, but it is not adequate for HTSC research, except for "retrospective" surveys. There are exciting new materials under intense study today that were still unknown 3 months ago. Moreover, papers being published today have been available as *preprints* for several months already; such is the publication delay of major journals. I therefore submit that INSPEC (and other computerized literature databases) do not serve the purpose I have in mind.

A Database is not a Library!

Moreover, one needs more than a list of papers relevant to the subject at hand; the desired information is not in the *list* but in *the papers themselves* — which none of the existing databases can provide. I have found advertisements for "manuscript delivery services" attached to the various literature databases, but in every case these are slower and more expensive than simply telephoning the authors (even abroad) and asking them to mail one a reprint.

Some of the papers on the computer's list may be available locally in the form of journal subscriptions at the institution's library, but this is no help to small companies;

and even UBC does not have all the relevant journals nor the most recent issues of any of them. In any case, the very fact that the paper has been published guarantees that it is several months out of date. In a field where breakthroughs come and go in a matter of weeks, this is useless.

A few of us are on mailing lists from other HTSC research laboratories; we each receive several unsolicited preprints every week; at UBC (and no doubt elsewhere) these actual physical copies of papers are collected into a huge pile and sorted as rationally as possible, so that we now possess our own large library of HTSC papers. The problem then becomes one of knowing which papers we have and where they are located, without sorting through thousands of them at each query.

A Luxury Service: the HTSC Remote Library

The only qualitative improvement upon this depressing situation would be an integration of a computer database like *SUPCON* with a HTSC Library containing the papers listed in *SUPCON*. Both would be maintained and operated by dedicated full-time personnel who would receive, sort, file and enter pre- and reprints collected by scientists and engineers in B.C. from their colleagues elsewhere. A competent and motivated Database Manager could continuously upgrade the search program to make it faster and more efficient, as well as to give it "intelligent" features such as "auto-weeding" of redundant entries. With enough personnel, the database could be expanded to include *abstracts* of the papers as well as titles, etc. It would be wise to design the database so that it can even contain the papers themselves (or at least the text thereof), for many scientists now prepare their work using text processing languages like TEX (in which this proposal is being written, for instance) and it is not uncommon for preprints to be transmitted over the computer networks to interested colleagues. We will probably not get many of these, but there should be room for them.

Users would be able to access *SUPCON* freely over BCnet and/or public telephone lines, find the papers of interest to them, peruse the abstracts on-line to select those of genuine interest, and issue a request for a hard copy where needed. The Librarian would then either copy the paper and mail it to the user or FAX it directly if the user has a FAX machine. The additional expense of copying and distribution would be a small fraction of the salaries of the Database Manager and Librarian. It is not clear whether copyright laws prevent such free distribution of *re*prints; but since the most important function of the Remote Library is to collect and make available unpublished *pre*prints, this is not a serious concern.

Such a facility would certainly be a luxury - one which is probably not available even to top research groups at giant corporate labs elsewhere. It would give our scientists and engineers an unfair advantage in a very glamorous and putatively profitable field. If this elitist proposition is distasteful, we could always make it available to everyone.

Tentative Configuration and Budget

A detailed design study of such a BC Database/Library on HTSC has not been attempted; however, it is easy to outline one possible implementation in round figures. I will describe a system based on a MicroVAX II computer and the INGRES database software, which is compatible with the present implementation of *SUPCON* on the TRIUMF VAXcluster under INGRES and would thus save certain startup costs (such as the insertion of the hundreds of papers already in TRIUMF's *SUPCON*). Several alternative computer systems should be considered, such as the Apollo or Sun workstations, but I do not know them well enough to compare their ease of remote use or available database facilities with those of VAX-VMS and INGRES. The most essential design criterion is the availability of "user-friendly" interactive features implemented on a variety of user terminals, ranging from "dumb terminals" to other computers running terminal emulation programs.

No matter what hardware implementation is chosen, several fixed and recurrent costs are easily forseen: a large disk and backup tape cartridge, a high-volume printer, a copy machine and a FAX machine, software license fees, a BCnet Ethernet interface, several dial-in modem lines, library and office space, and of course the salaries of the Database Manager and the Librarian. (In the first year, additional typists might be needed to enter the already-huge backlog of titles and abstracts.)

Fortunately, TRIUMF has offered to provide some of the necessary facilities, such as space, copying and FAX machines and possibly a printer; moreover, although TRIUMF cannot afford to allow its computing facilities to be overtaxed by *SUPCON* users, the initial development of the database could be continued on the TRIUMF VAXcluster until independent hardware is obtained, allowing the project to start as soon as personnel are hired.

Initial Funding (First Year)

Database Manager salary	$ 45,000
Librarian salary	$ 35,000
Full-time Typist salary	$ 25,000
VMS INGRES License	$ 8,000
MicroVAX II computer configuration	$ 35,000
1 GB disk and cartridge tape backup	$ 15,000
Maintenance and Materials costs	$ 10,000
Total	*$173,000*

Continuing Funding (Subsequent Years)

Database Manager salary	$ 45,000
Librarian salary	$ 35,000
VMS INGRES License	$ 8,000
MicroVAX II and peripherals Maintenance	$ 5,000
Lease of copy machine and FAX machine	$ 15,000
Maintenance and Materials costs	$ 10,000
Total	*$118,000*

A Pilot Project in Advanced Information Science?

This is a lot of money to gamble on a local return in profitable HTSC research. Of course, a successful HTSC industry in British Columbia would repay many times this investment annually in taxes; but a Remote Library has a long lever arm on commercial development and it would be hard to document its contribution in the long term. Moreover, it is likely that, once the HTSC Remote Library settled down to routine operation, its functions would not overtax the capabilities of the computer system or the Database Manager and Librarian. In this event it would be wise to consider adding new "information-critical" high technology topics to the mandate of the Remote Library. This is, it seems to me, well in keeping with the notion of supporting Information Science as a blossoming new "enabling technology" area in B.C., especially since this is an example of advanced Information Technology that is demonstrably useful to a well defined community who might profit immeasurably thereby.

There is no need to point out that I am stepping well outside the boundaries of my expertise. This is self-evident. However, as Richard Feynman is reputed to have said, "Science is the belief in the ignorance of experts." So I am in good company. On the other hand, while experts may be ignorant, they are rarely stupid; if this proposal is perceived to have any merit, I urge Council to immediately solicit the technical advice of experts in Library and Communications Science, as well as an unbiased consultant on computerized database hard- and software, to expose defects and hidden potentials in my amateur scheme.

Time is of the essence if this concept is to become reality soon enough to have any effect on the outcome of the HTSC race; moreover, the papers pile up just as fast whether or not anyone is sorting and filing them, so delays now will be paid for later.

SUMMARY OF RECOMMENDATIONS
FROM ALL SECTORS

AGRICULTURE AND FOOD PROCESSING

PRIMARY AGRICULTURE
- ROLE OF AGRICULTURE CANADA
- VERY SMALL AVAILABLE LAND BASE

SECONDARY MANUFACTURE
- POTENTIAL GROWTH AREA

FOOD PROCESSING
- POTENTIAL GROWTH AREA

RECOMMENDATIONS

- INTERFACE WITH BIOTECHNOLOGY
  - DISEASE CONTROL
  - GENETICS
  - WASTE MANAGEMENT

- VALUE ADDED
  - FOOD PROCESSING

- INCREASE PRODUCTIVITY

- INCREASE INDUSTRY INVOLVEMENT
  - CO-OPERATIVE RESEARCH

AGRICULTURE AND FOOD PROCESSING

RECOMMENDATIONS (CONT'D.)

- FUNDING FOR SECONDARY MANUFACTURE, FOOD PROCESSING
- RESEARCH ORGANIZATIONS STAFFING AND EQUIPMENT
- GENERAL AWARENESS
- TECHNOLOGY TRANSFER

AQUATIC RESOURCES

$750M INDUSTRY

AQUACULTURE - HIGH GROWTH
- SCIENCE ISSUES

RECOMMENDATIONS

- WATER QUALITY
  - SPECIFIC CONTAMINANTS
  - AQUACULTURE
- AQUATIC INSTRUMENTS AND DEVICES
  - INTERFACE WITH SECTOR
  - GROWTH AREA
- FISH HARVESTING
  - GOVERNMENT AND SOCIAL POLICIES
  - IMPROVEMENTS POSSIBLE
  - SHIP/SHORE COMMUNICATION

AQUATIC RESOURCES

RECOMMENDATIONS (CONT'D.)

- FISH PROCESSING
  - NEW PRODUCTS
  - BY-PRODUCTS
  - QUALITY
  - PACKAGING
- AQUACULTURE
  - INTERFACE WITH BIOTECHNOLOGY
    - DISEASE CONTROL
    - NUTRITION
    - GENETICS
    - WASTE MANAGEMENT
  - NETWORK OF EXCELLENCE

BIOTECHNOLOGY

EMERGING INDUSTRY - $12M

IMPACTS ON MANY SECTORS
- FORESTS
- AGRICULTURE
- AQUACULTURE
- HEALTH
- WASTE MANAGEMENT
- MINING

NEED FOR STRATEGIC PLANNING, CO-ORDINATION

RECOMMENDATIONS

- FOCUS ON
    - DISEASE CONTROL
    - GENETIC IMPROVEMENT
    - WASTE MANAGEMENT
- STRATEGIC PLANNING - USE OF EXISTING COMMITTEE
- LONG TERM COMMITMENT OF FUNDING
- RAISE FUNDING FROM $10M TO $30M - 5-10 YEARS

BIOTECHNOLOGY

RECOMMENDATIONS (CONT'D.)

- STRATEGIC RESEARCH, TRAINING, SCHOLARSHIPS
- INDUSTRY/UNIVERSITIES INTERACTION
- REVIEW FACILITIES NEEDS AND CO-ORDINATION

ENERGY

MAJOR RESOURCE OF PROVINCE

DEPENDENCE OF OTHER RESOURCE SECTORS

OIL - IMPORT TO B.C.

NATURAL GAS SURPLUS

RECOMMENDATIONS

- OIL & GAS
  - DEVELOP UNDERSEA ROBOTICS
  - PREPARE FOR SWITCH AWAY FROM OIL
  - NATURAL GAS DIESEL ENGINE CONVERSION
- COAL
  - DEVELOP CAPABILITY TO ANALYZE COALS
  - BENEFICIATION & TRANSPORTATION
  - ALTERNATIVE USES

ENERGY

RECOMMENDATIONS (CONT'D.)

- WOOD RESIDUE AND BIOMASS
  - CONTINUE DEVELOPMENTS - METHANOL, ETHANOL
- OTHERS
  - HYDROGEN
  - FUEL CELL

SCIENCE & TECHNOLOGY ENERGY FOCUS

- CENTRE FOR ENERGY STUDIES
- BUILD EXPERTISE
- UNDERTAKE TESTS
- NATURAL GAS
- LONGER TERM ITEMS

FORESTS AND FOREST PRODUCTS

GROWTH AREA

MOVING TO VALUE ADDED PRODUCTS

RESOURCE DIMINISHING AND MORE EXPENSIVE

WORLD-WIDE COMPETITION

DEPENDENCE ON SCIENCE & TECHNOLOGY

ADVANCED MACHINERY AND SYSTEMS

PEOPLE NEEDS

RECOMMENDATIONS

- OVERALL CO-ORDINATION FOR SCIENCE AND TECHNOLOGY
- ADD VALUE
- IMPROVE PRODUCTION FOR RESOURCE

Science Council of British Columbia

Helping Make Tomorrow Happen in B.C.

FORESTS AND FOREST PRODUCTS

RECOMMENDATIONS (CONT'D.)

- RAISE TECHNOLOGICAL AWARENESS AND COMPETENCE
    - RESEARCHERS
    - 'RECEPTORS'
- TECHNOLOGY TRANSFER
- USE OF ADVANCED SYSTEMS, TECHNOLOGIES AND MACHINERY

INFORMATION TECHNOLOGY

$1 BILLION INDUSTRY

11,500 PEOPLE

25%-50% ANNUAL GROWTH

RESOURCE INDUSTRIES/INFORMATION TECHNOLOGY

PEOPLE NEEDS

CO-ORDINATED ACTIONS

RECOMMENDATIONS

- ENHANCE RESOURCE INDUSTRIES BY ENHANCING THE INFORMATION TECHNOLOGY INDUSTRIES
- COMMIT TO INFORMATION TECHNOLOGY
- MARKETING, MANAGEMENT, TECHNICAL PEOPLE
- CO-ORDINATION AND PLANNING ROLE
- INFRASTRUCTURE AND SUPPORT

MANUFACTURING

IMPORTANCE TO PROVINCE

4,000 COMPANIES - 40 LARGE

LACK OF TRAINING

DIFFICULTIES OF LOCATING PARTNERS

TECHNOLOGY TRANSFER - SMALL COMPANIES

RECOMMENDATIONS

- STRATEGIC PLAN - 'CHAMPION'
- BIOMEDICAL DEVICES
- EDUCATION AND TRAINING
- TECHNOLOGY CENTRE
- RESOURCE INDUSTRIES - ROBOTICS
- NETWORKING
- CAD/CAM
- FUNDING

MINING, MINERALS, METALS

NEEDS

- INDUSTRY INVOLVEMENT
- NATIONAL CO-ORDINATION
- FOCUS ON R&D
- RAISING AWARENESS

RECOMMENDATIONS

- R&D CO-ORDINATOR FOCUSSED ON B.C. NEEDS, NATIONAL INTERFACE

- INDUSTRY CHAIRS - ADVANCED MATERIALS

- CENTRES OF EXCELLENCE:

  - ADVANCED MATERIALS
  - INDUSTRIAL MINERALS
  - GEOLOGICAL EXPLORATION
  - RARE & PRECIOUS METALS

EMERGING THEMES

- BUILD ON EXISTING COMPANIES, ORGANIZATIONS AND INDIVIDUALS
- ORGANIZED STIMULATION OF INTERACTION AND PLANNING WITHIN AND BETWEEN SECTORS
- RESOURCE INDUSTRY FOCUSSED, TECHNOLOGY DRIVEN CENTRES OF EXCELLENCE
- VALUE ADDED PRODUCTS FROM RESOURCES USING TECHNOLOGY DEVELOPED IN B.C.
- DEVELOP THE MARKETING, MANAGEMENT AND TECHNICAL TALENTS OF OUR PEOPLE
- EFFECTIVE USE OF SIGNIFICANTLY MORE R&D SPENDING